VOLUME 8 March 1959 NUMBER 2 (PART 2)

(In Two Parts)

THE AMERICAN JOURNAL OF

Tropical Medicine and Hygiene

Combining The American Journal of Tropical Medicine and The Journal of the National Malaria Society

OFFICIAL ORGAN OF
THE AMERICAN SOCIETY OF TROPICAL MEDICINE AND HYGIENE

PUBLISHED BIMONTHLY BY
THE WILLIAMS & WILKINS COMPANY
BALTIMORE 2, MARYLAND, U.S.A.

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Malaria in Oases of Eastern Saudi Arabia

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MALARIA IN OASES OF EASTERN SAUDI ARABIA[1]

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Malaria has long been recognized as a primary health hazard in many Saudi Arabian communities. It is of particular importance throughout the Arabian peninsula wherever special concentrations of population are found in and around oases. These oases with their springs, wells, and associated irrigation schemes often offer ideal breeding places for vector anophelines. The resultant close overlap of host and vector populations, plus favorable climatic conditions, may lead to sharply localized but intense malaria transmission.

Nowhere is this potential malaria hazard more apparent than in the oases of eastern Saudi Arabia. Here, climate, economic conditions, housing, topography, agriculture, irrigation practices, anopheline fauna, and educational level of the population all contribute to a very high endemic potential for this important disease. Thus malaria is a very real threat to future economic development and industrial progress in the Eastern Province of Saudi Arabia. In order for industry and agriculture to progress most effectively, malaria and other major disease problems must be controlled.

It is axiomatic that any realistic plans for malaria control must be based on a careful study of the local epidemiology of the disease. No scientific study of oasis malaria has previously been reported for eastern or central Saudi Arabia even though the disease has been recognized for centuries as a major public health problem in this area. References to "oasis fever" and "Gulf fever" are frequent in the accounts of early travelers, explorers, geographers and other observers who have visited the area (Buxton, 1944). Scattered notes on malaria occur in more recent reports of health conditions in the Persian Gulf region as a whole. But the local epidemiology of the disease in these oases has not been studied previously, and no earlier attempts at control have been made.

The present study was initiated indirectly by the interest of the late King, Abdul-Aziz Ibn Abdul-Rahman Ibn Faisal Al-Saud. With the early development of the Saudi Arabian oil fields and introduction of modern technology came a desire for improvement in general health and medical care. The King, having recognized the importance of malaria as a basic health problem in the region, requested the assistance of the Arabian American Oil Company in making surveys and developing plans for control of the disease.

As a result of this interest, the present study was begun by the writer in the summer of 1947. It is based primarily on surveys and observations in the Qatif and al-Hasa oases on the Persian Gulf coast. Additional information was gathered from briefer surveys in the interior at Yabrin and in the al-Kharj district just south of Riyadh. The present report summarizes 11 years of local study and experience in malaria survey and control with the hope of presenting a sound basis for a more intensive attack on the malaria problem in the future. Ultimately, it is hoped, malaria eradication can be achieved in these two oases of the Eastern Province if both individual citizens as well as communities cooperate in a joint, intelligent attack on the problem.

PART I. ECOLOGY OF THE STUDY AREA

The Eastern Province of Saudi Arabia (al-Hasa province of some authors) includes that part of the Kingdom located along the Persian Gulf between Kuwait and Trucial Oman, excepting the thumb-like Qatar peninsula (Fig. 1). To the interior, the Eastern Province is separated from the Najd by a great belt of active sand dunes known as the Dahna. To the south of the province lies the famous Rub' al-Khali or Empty Quarter.

[1] Contribution from the Department of Tropical Public Health, Harvard School of Public Health. This paper represents part of a thesis submitted as a requirement for the degree of Doctor of Public Health, Harvard University.

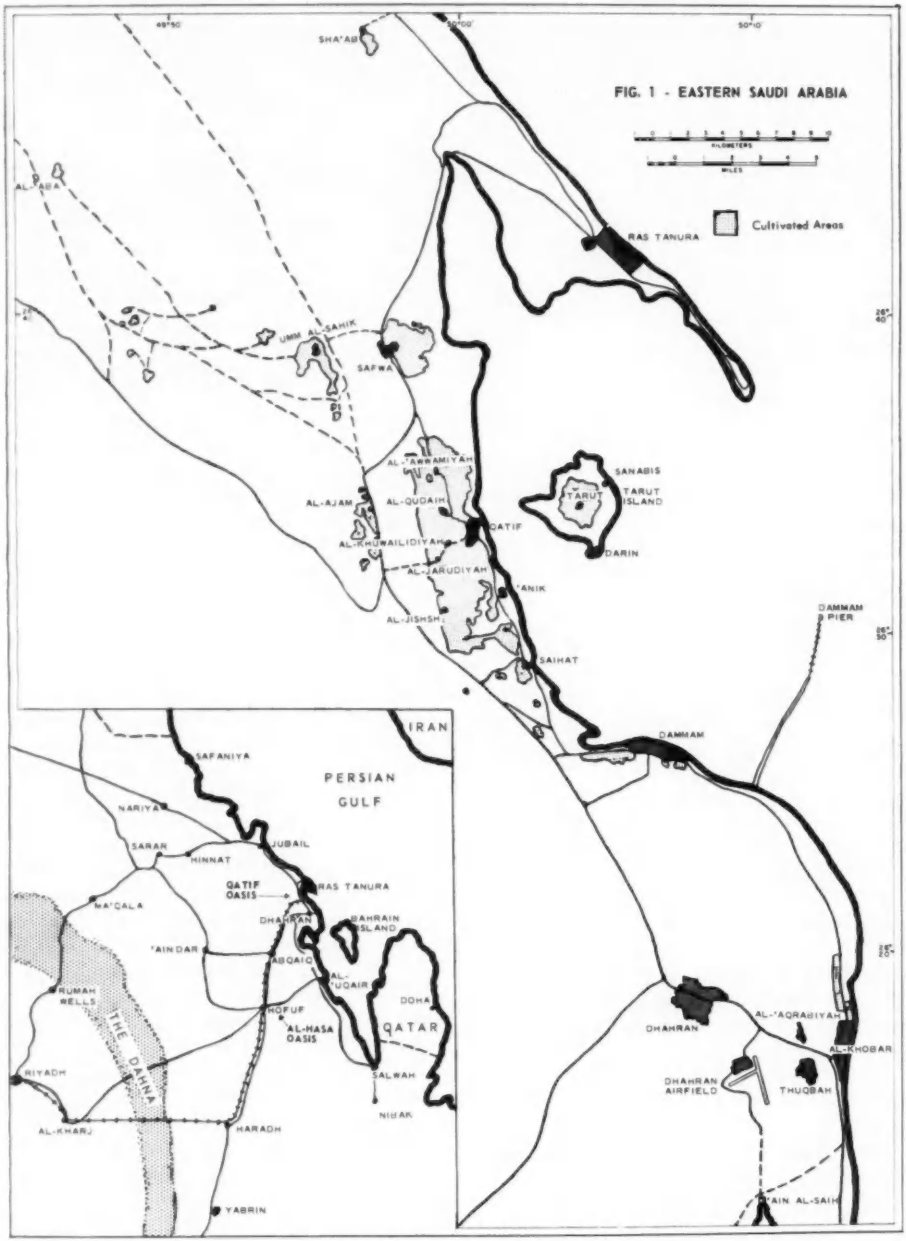

FIG. 1. Eastern Saudi Arabia

Within this general region the topography is usually low and flat along the coast. Further inland are low rolling sand ridges with scanty shrubs and other sparse xerophytic vegetation. Interspersed are occasional escarpments of flat, rocky terrain with isolated buttes and mesas. Areas of gravel plains and actively drifting sand complete the general picture. No part of this coastal region is more than a few hundred feet above sea level, but the elevation of the country as a whole gradually increase towards the interior.

Malaria is strictly confined to the irrigated oasis areas in this typical desert environment. The two most important oasis areas are the al-Hasa oasis at Hofuf about 40 miles inland from the Gulf and the Qatif oasis about 15 miles north of Dhahran (Fig. 1). With minor exceptions, these two oases present similar problems from the malaria standpoint. Here oasis malaria is characterized by its sharp delimitation to island-like cultivated areas in a sea of sand (Figs. 1 and 2). The oasis population is concentrated in one or two main centers and the remainder in scattered small villages surrounded by irrigated date palm groves. Within this area are also concentrated the breeding places of the anopheline vectors; primarily *Anopheles stephensi*. Hence, man, mosquito, and parasite are all closely confined to the cultivated areas; and here malaria is hyperendemic. A few miles from the well defined borders of these oases, Bedouins or other travelers are relatively safe from the disease.

The three main Arabian American Oil Company (Aramco) communities, Dhahran, Abqaiq and Ras Tanura, are too distant from mosquito breeding places to be included within the effective flight range of local anophelines. Hence, Aramco's malaria problem is almost wholly confined to its Saudi Arab employees who live in, or commute to and from, these oasis areas. The great majority of the present 13,000 Saudi Arab Aramco employees are townsmen, less than 3,000 are Bedouins. A large proportion of these townsmen have their homes and families in the oases we have just described, and many of the Bedouin employees are bringing their families into satellite communities nearby.

PROVINCIAL POPULATION

No census has ever been taken in the Eastern Province, hence the total population is unknown. Rough estimates of the provincial population are given in Table 1, but it must be emphasized that these are crude figures. Data from Vidal (1955) are given for al-Hasa. Estimates for the coastal area are derived from a variety of sources including aerial photographs, number of houses sprayed in 1955, and personal estimates by various individuals. As can be seen in Table 1, the majority of the population is settled in towns or villages and only about one-seventh are nomadic Bedouins. The great bulk of this settled population (310,000) lives in or near the two main oases and hence is subjected to a greater or lesser degree to malarial infection. The intensity of malarial attack in the population is directly proportional to its nearness to irrigated agricultural areas which provide the breeding places for vector anophelines.

Qatif Oasis

The Qatif oasis proper occupies a rather solid core of 10,000 acres arranged in a rectangular strip about 8 miles long and 3 miles wide. Its long axis parallels the seacoast, its pivot point being the city of Qatif. About 7,000 acres in this central core are devoted to cultivation of dates; other acreage is in general garden cultivation, some in village sites, and the remainder in sandy or water-logged wasteland. Smaller scattered oasis plots exist along the 60-mile coastal strip from al-Khobar and Dammam on the south to Safwa, Umm al-Sahik, al-'Aba, Sha'ab, and Jubail to the north. Additional oasis areas are also found at al-Ajam immediately to the west and on Tarut Island to the east.

For purposes of this report, all of the above cultivated areas are related malariologically and will be included in our broader definition of the "Qatif" oasis. Some 30 towns and villages are found in this coastal area with a total population of about 150,000. As in the al-Hasa oasis, the more numerous smaller villages are primarily agricultural communities with some fishing and pearling in the case of those located directly on the sea. Al-Khobar, Dammam, and Jubail are important coastal trading centers, lie outside the dense palm belt, and hence are less malarious. Qatif, the largest city in the oasis proper, is an ancient trading center and is located almost at the center of the garden area (Fig. 3).

al-Hasa Oasis

The oasis of al-Hasa is famous throughout the country as the largest single oasis in the entire

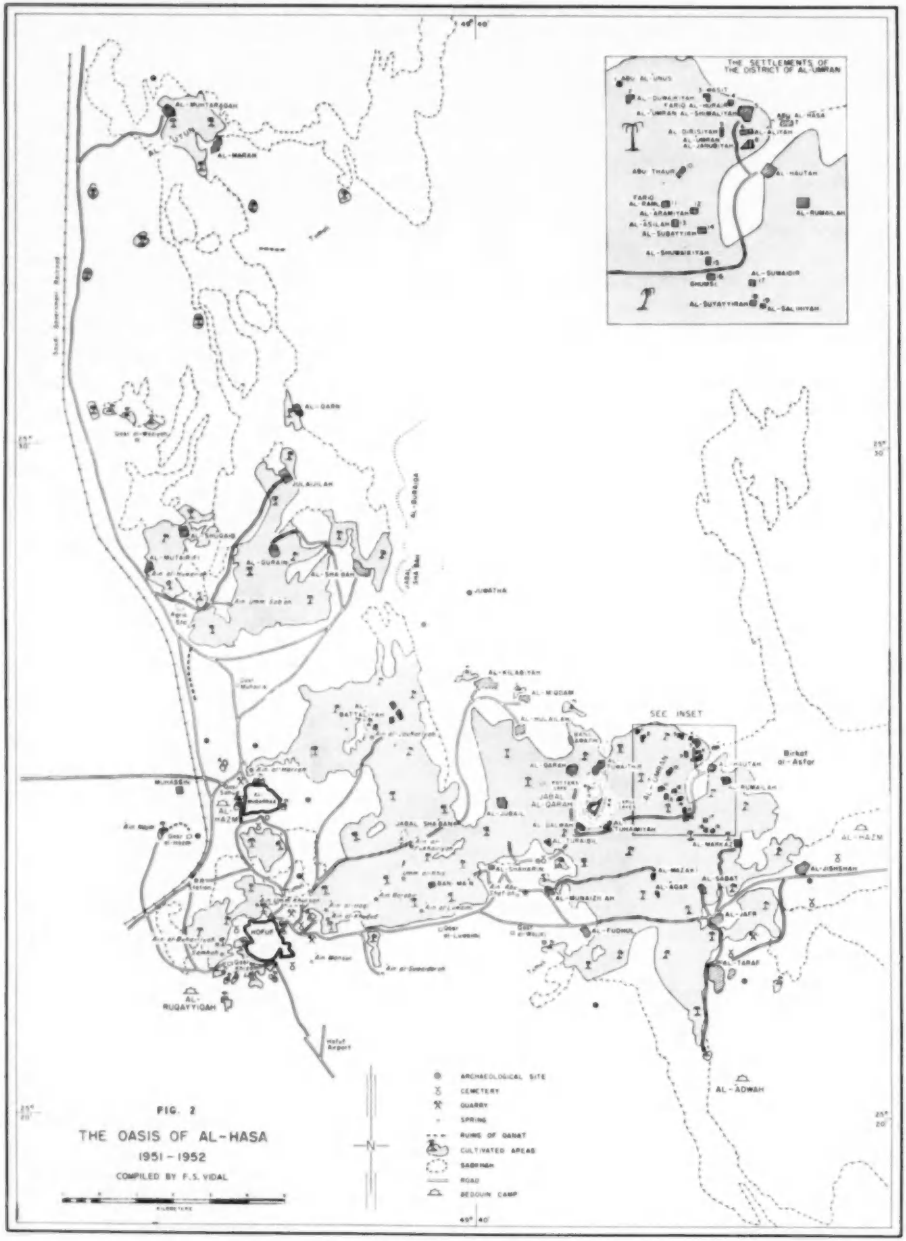

FIG. 2. The oasis of al-Hasa

TABLE 1

Eastern Province population estimates

Bedouin (nomad) population	50,000
Settled population	310,000
Eastern Province total	360,000

I. Coastal Settled Population			150,000
A. Trading centers		55,000	
Dammam	30,000		
al-Khobar	20,000		
Jubail	5,000		
B. Aramco communities & satellites		35,000	
Dhahran	12,000		
Abqaiq	5,000		
Ras Tanura	5,000		
Thuqbah	11,000		
al-'Aqrabiyah	2,000		
C. Qatif Oasis		60,000	
Qatif	18,000		
Safwa	5,400		
Saihat	4,800		
Umm al-Sahik and adjoining settlements	4,800		
Tarut	4,000		
al-'Awwamiyah	3,600		
al-Qudaih	3,600		
Sanabis	3,000		
Darin	2,400		
'Anik	1,800		
al-Jishsh	1,800		
al-Jarudiyah	1,800		
al-Khuwailidiyah	1,300		
al-Ajam	1,100		
Other smaller villages	2,600		
II. Interior Settled Population al-Hasa Oasis			160,000
A. Trading centers			
Hofuf		60,000	
al-Mubarraz		28,000	
B. Garden villages		72,000	
al-Taraf	3,700		
al-'Umran al-Shimaliyah	2,400		
al-Jishshah	2,200		
al-Qarah	2,200		
al-Fudhul	2,100		
al-Battaliyah	2,100		
al-Jafr	2,000		
al-Muhtaragah	1,700		
Other smaller villages	53,600		

Arabian peninsula. Together with the Qatif oasis, it forms the most important agricultural area in the Kingdom. Al-Hasa is located about 100 miles south of Dhahran and about 40 miles inland from the Persian Gulf port of al-'Uqair. The oasis is roughly L-shaped, about 15 miles in length on the long axis and 10 miles on the shorter axis, and includes an estimated 30,000 acres under cultivation.

Although no census figures are available, the total population of the oasis is estimated by Vidal (1955) at 160,000. From this he calculates an average population density of 2,300 per square mile. Hofuf, the largest city, is rated at about

FIG. 3. City of Qatif with surrounding date palms

FIG. 4. *Stephensi* pond with adjacent village (Qatif oasis)
(Photo by E. E. Seal)

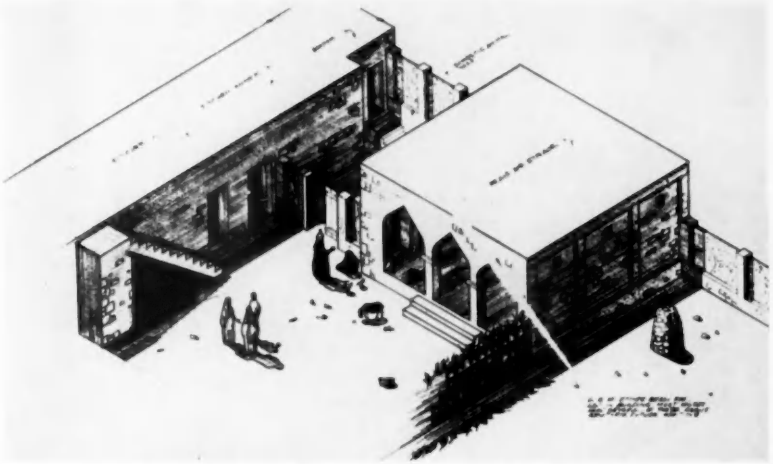

FIG. 5. Types of oasis housing—masonry construction

60,000; al-Mubarraz at 28,000. The remainder of the population (72,000) is distributed among 52 villages and smaller settlements scattered throughout the oasis. These are primarily agricultural communities, varying in size from larger villages of 3,700 to small hamlets. Malaria, as might be expected, is an important problem in those smaller agricultural communities in close contact with irrigated areas and is less intense in the larger trading centers of Hofuf and al-Mubarraz (Fig. 4).

HOUSING

The better houses (Fig. 5) in the villages are often two-storied buildings built of limestone rubble, mud brick, or a marine conglomerate. Some have a mud finish, others are plastered with gypsum cement ("juss"). Ceilings are generally high, of black painted mangrove, palm, or ithl rafters overlaid with fine matting and mud. In the al-Hasa villages, mud brick predominates. In the Qatif oasis, the adobe is largely replaced with a local marine conglomerate readily available from the sea.

"Barastis" (Fig. 6) are commonly used as dwellings by the poorer families. These are usually simple huts made of a pole and palm-trunk framework covered with palm-thatch and usually without windows. All degrees of variation from the simplest barasti to the larger masonry houses may be found in the villages. In the larger towns, modern homes and apartment buildings may be found equipped with all utilities, even including unit air conditioners.

AGRICULTURE

Dates are of first importance as a crop in both oases. Alfalfa and rice are also cultivated in quantities. Other fruits include figs, pomegranates, bananas, peaches, apricots, citrons, limes, grapes, and papaya. Eggplant, okra, tomatoes, melons, cucumbers, onions, cabbage and a few others are grown as vegetable crops. Cereals such as sorghum, millet, barley, and wheat are found in addition to rice.

Livestock of the area comprises donkeys, some cattle, goats, and poultry. Sheep and camels are kept by the Bedouin in the nearby desert areas but are not common in the oasis proper.

IRRIGATION PRACTICES

In general, irrigation practices and water management problems are the same in both oases. Al-Hasa is supplied with irrigation water by some 50 to 60 springs with an estimated total discharge of 150,000 gallons per minute. Four of these al-Hasa springs are very large, their individual flows estimated at 20,000 gallons per minute. More recently, a few drilled artesian wells have been added; but the main al-Hasa irrigation sources are the natural, flowing springs.

In both oases, water from these sources flows in guided channels following the natural slope of the terrain. The larger gardens, consisting pri-

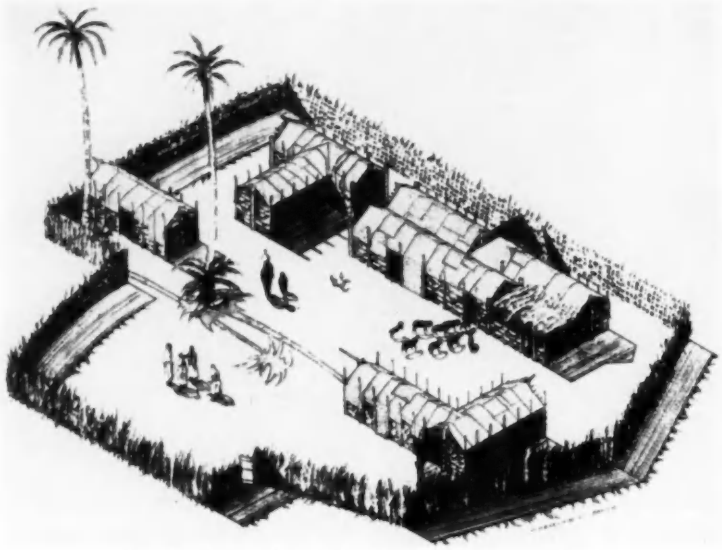

FIG. 6. Types of oasis housing—barasti compound

marily of dates and rice, are irrigated by this gravity flow. Smaller plots devoted to production of alfalfa and vegetables may be irrigated by lifting water onto the plots by donkeys or by various mechanical devices from the major irrigation channels.

In most cases, drainage ditches are needed to draw off surplus irrigation water; and this water, concentrated in larger drainage canals, may be used again at lower levels. Ultimately, the excess runs off into the desert, accumulates on the "sabkhas" (salt flats) surrounding the palm belts, or runs to the sea as in the case of most Qatif oasis drainage.

These irrigation systems thus form an extremely complex network of irrigation channels and drainage ditches. The frequency of irrigation and length of time of flow vary with season, size of garden, and distance necessary for water transportation. Complex schedules of irrigation are often in force, and the involved water rights of various property owners make general control of irrigation waters difficult.

The present systems are not efficient from the point of view of modern agricultural engineering. There are miles of unnecessary ditches, and many are improperly constructed so that large amounts of water are lost through seepage or over flow. In the Qatif oasis, drilled artesian wells are much more frequent. In many instances, these wells have not been properly cased and are not fitted with control valves. The ceaseless flow from uncontrolled wells and leakage of water from those improperly constructed merely add to the already complex water problem in the low-lying Qatif area.

As a result of the complexity of the irrigation system, its inefficient construction, and excess water wastage, large areas of agricultural land have become water-logged in both oases. This becomes even more apparent in the winter months when the need for frequent irrigation becomes lessened and the rate of evaporation decreases. With this water excess and poor drainage the ground water table becomes too high for good agricultural practice. As a consequence, not only is much potentially productive land lost, but favorable habitats for malarial mosquities are greatly increased.

CLIMATE

The intense heat of the summer months is the most widely known feature of the Arabian climate. The summer months from June through September are unusually hot, July temperatures along the coast reaching 116° F. At Dhahran,

TABLE 2

Mean monthly temperatures, Ras Tanura, 1945–1956

Month	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	Average
January	—	61.7	63.2	60.2	57.5	56.1	62.7	59.8	65.5	60.1	60.8	60.0	60.7
February	59.0	61.0	61.8	63.1	58.2	56.0	62.6	64.8	64.4	63.9	64.0	64.3	61.9
March	64.0	72.0	68.1	65.9	67.1	65.8	67.2	69.0	66.4	68.6	69.5	70.1	67.8
April	75.0	74.7	76.3	74.4	72.6	75.6	76.9	78.2	77.6	78.4	76.8	75.4	76.0
May	84.0	84.3	83.7	84.3	83.4	83.3	85.9	86.5	86.1	84.9	84.8	79.9	84.3
June	91.3	87.4	88.9	89.5	89.1	87.5	91.2	88.8	89.3	90.3	89.8	86.7	89.2
July	93.2	90.1	93.0	91.8	91.3	91.7	95.2	92.4	93.0	94.1	91.8	92.6	92.5
August	93.2	90.2	89.6	92.1	91.7	92.0	93.5	93.5	92.2	95.5	92.2	93.8	92.5
September	89.2	87.7	86.2	85.9	84.1	87.7	90.8	90.5	88.3	90.5	87.1	89.1	88.1
October	83.1	80.3	82.0	76.9	77.3	83.8	84.3	81.9	85.3	84.2	80.2	80.7	81.7
November	74.6	72.5	76.5	71.0	70.5	78.1	71.4	72.7	73.8	78.2	75.5	70.1	73.7
December	67.5	66.2	63.8	63.7	64.7	65.0	63.8	66.4	60.1	67.4	65.2	63.8	64.8
Mean annual temperature	79.5	77.3	77.8	76.6	75.6	76.9	78.8	78.7	78.5	79.7	78.1	77.2	77.8

only a short distance inland, 121° F has been recorded, and even higher temperatures are experienced farther inland. The unpleasantness of the hot summers is further aggravated by high humidity during the latter part of this period. The nights, in particular, may be humid and oppressive. Strong winds, commonly from the north ("shamals"), are most prevalent in June and July and serve to mitigate the unpleasant effects of high temperatures. The shamals may be accompanied by sand or dust storms. By contrast, the weather from November through April is usually very pleasant with cool nights and sunny, balmy days. Wind storms are much less frequent during this period. Rainfall is very sparse (averaging only 3 inches per year), often erratic, and usually limited to short periods between November and April. Of special malariological interest locally is the seasonal-high-humidity strip along the western margins of the Persian Gulf. It is in this strip that the Qatif and al-Hasa oases are located.

Source of Weather Data

In our present study, we have used weather data collected by Aramco at Ras Tanura to study the effects of local climate on malaria transmission. It was felt that Ras Tanura records would more nearly approximate actual conditions in the Qatif oasis than would similar data from Dhahran. Hence the tabular presentations of temperature, relative humidity, and rainfall data are all calculated from raw data collected at Ras Tanura (for comparable Dhahran data, see Tarizzo (1957)).

Temperature. Temperature data from this source are summarized on a weekly and monthly basis for the period February, 1945 through December, 1956. The greatest seasonal extremes in daily temperatures during this 12-year period range from a minimum of 36° F (Jan. 30, 1950) to a maximum of 116° F (July 5, 1945). At the Dhahran airport, July temperatures of 121° F have been recorded, and even higher summer temperatures are noted in the interior. Daily mean temperatures at Ras Tanura have ranged from 43° F (Jan. 27, 1950) to 102° F (July 13, 14, 1951; Aug. 4, 1956). A composite of mean monthly temperatures, 1945 through 1956, is given in Table 2.

Relative humidity. Data on relative humidity (RH) were also analyzed. There is a tremendous range in RH from a minimum of 0% to frequent recordings of 100%. Mean monthly RH were calculated on the basis of daily readings taken at 0900 hours from February, 1945 through August, 1949. After that date, only daily maxima and minima were recorded. These were averaged to give a mean daily RH (September, 1949 through December, 1956). Composites of mean monthly RH based on 0900-hour readings (Table 3) and as well as those based on daily averages (Table 4) are included below.

For a more exact analysis of seasonal shifts in temperature and RH, weekly means were calcu-

TABLE 3

Mean monthly relative humidities calculated from 0900 readings, Ras Tanura, 1945–1949

Month	1945	1946	1947	1948	1949	Average
January		78.1	74.8	78.5	73.5	76.2
February	68.3	81.4	75.6	79.7	58.5	72.7
March	73.1	72.6	75.0	64.5	62.2	69.5
April	69.0	68.2	55.9	63.3	57.3	62.7
May	60.9	57.8	65.8	56.2	50.5	58.2
June	58.4	47.1	67.1	40.8	42.7	51.2
July	60.2	45.9	53.5	47.4	49.9	51.4
August	57.9	41.4	59.9	47.7	43.5	50.1
September	64.7	55.5	58.8	54.5		58.4
October	71.9	60.8	72.7	54.2		64.9
November	74.3	71.9	77.6	70.6		73.6
December	77.4	75.0	78.2	83.1		78.4

lated. These data are plotted later in conjunction with seasonal studies on malaria morbidity.

Rainfall. Rainfall is scanty, averaging 3 inches per year, and is usually confined seasonally to late winter and early spring. Summers are usually completely rain free. The monthly distribution of rainfall, and annual totals, are given in Table 5. The quantities are so small that rainy seasons, as such, have almost no effect on extending mosquito breeding areas. Hence, rainfall is of little or no importance in determining either the extent or the seasonal cycle of malaria in eastern Saudi Arabia.

Standard Weather Pattern

From a 12-year analysis of available weather data (1945 through 1956), a standard annual

TABLE 4

Mean monthly relative humidities calculated from daily means, Ras Tanura, 1949–1956

Month	1949	1950	1951	1952	1953	1954	1955	1956	Average
January		77.4	63.8	74.6	67.1	73.6	82.4	69.4	72.6
February		68.1	83.3	77.2	69.6	72.8	71.5	70.6	73.3
March		68.5	77.2	71.4	62.9	67.5	74.7	75.8	71.1
April		61.1	69.9	69.3	62.9	57.0	64.5	69.1	64.8
May		54.9	75.5	57.0	50.1	52.1	61.6	57.6	58.4
June		44.1	82.9	47.2	49.1	46.3	59.6	47.3	53.8
July		58.6	74.1	46.3	53.7	58.8	60.9	54.5	58.1
August		62.2	69.8	50.7	54.9	64.0	63.1	57.9	60.4
September	63.7	69.5	75.4	60.6	60.7	64.4	56.1	61.4	64.0
October	65.8	55.6	64.4	62.5	64.5	70.8	60.9	61.4	63.2
November	72.6	56.8	66.7	62.4	71.9	75.8	71.5	59.2	67.1
December	83.0	52.5	71.3	66.0	77.9	80.4	71.0	69.5	71.5

TABLE 5

Rainfall in inches, Ras Tanura, 1945–1956

Month	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	Average
January	—	0.04	0.25	0.13	0.40	0.05	0.42	0.73	0.08	0.01	3.03	1.49	0.60
February	—	Trace	0.55	0.85	0.10	Trace	0.79	Nil	0.34	2.77	Nil	0.03	0.49
March	—	0.42	0.55	1.04	0.45	0.42	0.55	0.09	0.24	0.60	3.67	0.17	0.75
April	—	Nil	Nil	0.38	0.10	Trace	Nil	1.17	0.04	Trace	Trace	0.28	0.18
May	Nil	Nil	0.37	Nil	Nil	0.07	0.02	0.35	Nil	Nil	0.05	Nil	0.07
June	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
July	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
August	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
September	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
October	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Trace	Nil	Nil	Nil
November	Trace	Nil	0.71	Nil	1.05	Nil	Nil	Trace	Nil	0.30	Nil	Nil	0.17
December	Trace	Trace	0.08	1.04	1.72	0.07	0.62	0.13	5.19	2.30	1.72	0.79	1.14
Total annual rainfall		0.46	2.51	3.44	3.82	0.61	2.40	2.47	5.89	5.98	8.44	2.76	3.23

TABLE 6

Standard weather pattern for the Qatif Oasis based on Ras Tanura data, 1945–1956

Month	Week	Mean temperature	Mean relative humidity (0900 readings)†	Mean relative humidity (daily averages)‡	Mean monthly rainfall
		°F	%	%	in.
January*	(1)	61.0	77.4	69.8	
	(2)	60.6	76.3	73.8	
	(3)	60.8	76.5	73.6	
	(4)	60.5	75.0	72.9	0.60
February*	(1)	62.2	73.6	74.8	
	(2)	61.2	73.4	76.7	
	(3)	62.0	70.4	70.3	
	(4)	63.6	72.2	71.6	0.49
March*	(1)	65.7	73.0	74.0	
	(2)	67.0	66.8	71.9	
	(3)	67.3	66.6	73.7	
	(4)	70.0	67.5	66.7	0.75
April	(1)	72.0	65.2	63.3	
	(2)	75.4	63.9	63.8	
	(3)	77.0	61.3	64.9	
	(4)	78.8	60.9	63.6	0.18
May	(1)	81.8	61.4	63.8	
	(2)	82.5	60.7	59.7	
	(3)	85.3	56.5	54.1	
	(4)	86.4	56.8	56.7	0.07
June	(1)	88.2	56.8	53.9	
	(2)	88.7	54.4	53.0	
	(3)	89.1	51.9	54.6	
	(4)	90.3	44.3	53.7	nil
July	(1)	91.6	46.3	54.9	
	(2)	92.1	56.0	57.1	
	(3)	92.9	52.6	57.3	
	(4)	93.2	50.8	61.8	nil
August	(1)	94.1	47.8	57.1	
	(2)	92.3	44.0	59.3	
	(3)	92.6	51.5	61.1	
	(4)	91.4	55.0	62.9	nil
September	(1)	90.1	63.1	65.1	
	(2)	89.2	59.5	64.6	
	(3)	87.4	53.6	61.9	
	(4)	86.3	57.3	64.3	nil
October	(1)	84.5	69.0	61.4	
	(2)	83.0	65.6	63.9	
	(3)	81.3	59.2	64.7	
	(4)	79.1	69.2	63.2	nil
November	(1)	77.2	70.2	66.6	
	(2)	75.4	72.8	66.1	
	(3)	72.3	70.7	66.6	
	(4)	72.1	79.3	68.1	0.17
December	(1)	67.4	76.8	69.7	
	(2)	65.1	80.4	69.4	
	(3)	64.6	81.5	71.8	
	(4)	62.9	76.1	74.0	1.14
					3.23

weather pattern by weeks has been constructed (see Table 6 and Fig. 15). Weekly mean temperatures, weekly mean RH (from 0900 readings, 1945 through 1949; from daily averages, 1949 through 1956), and average monthly rainfall have been utilized in constructing a standard pattern for an "average year."

Temperature patterns are remarkably constant. From lowest weekly averages (60° F) in late January, mean weekly temperatures gradually increase until the last week of July and first week in August when maxima of 93 to 94° F are reached. From this peak, temperatures gradually decline until the coldest temperatures of late January are resumed. Throughout the 12 years studied, relatively little variation has occurred in this temperature pattern. Only rarely do weekly mean temperatures in any one year vary more than 5 to 6° from the standard 12-year average.

Relative humidities, on the other hand, vary a great deal. First, there are remarkable extremes (2% to 100%) in any one 24-hour period. Hence, daily averages and weekly means developed from them tend to obscure these differences. In an attempt to trace a more definite seasonal pattern of humidity change, 0900 readings were analyzed from April 1945 through August 1949 (at this time 0900 readings were discontinued). When these are averaged by weeks, more definite seasonal trends begin to emerge. From a study of 0900 weekly means in the table, it can be seen that the highest humidities roughly coincide with the lowest temperatures in December and January. There is a gradual decrease in RH with warmer temperatures until July and August when highest temperatures are accompanied by lowest RH. But the greater variations in RH make the seasonal humidity pattern much less constant than the corresponding temperature pattern. The seasonal pattern of precipitation, like that of temperature, is also remarkably constant; but the amounts of rainfall vary considerably from year to year.

Microclimates

Microclimatic variation does occur, but little is known about microclimates which might affect the vector population specifically. The influence of various types of housing on indoor temper-

* Except January–March, 1945.

† Data from April, 1945, through August, 1949.

‡ Data from September, 1949, through December, 1956.

atures and the local effects of permanent and temporary collections of surface water such as pools, wells, and "sabkhas" would be of special interest. A few observations on temperatures inside and outside mosquito-resting places during the hottest part of the summer may be of interest here. When outdoor shade temperatures (4 ft. above ground) were recorded at 111° F, ground-level floor temperatures in a barasti were noted at 100° F. (Saihat, midday, July 3, 1948). Later this same day, shade temperature in the Qatif palm gardens was recorded at 101° F while the ground temperature inside a barasti was 100° F. Inside a barasti near al-Khobar, a temperature of 103° F was recorded while in mosquito-resting niches in a stone wall (forming a part of the barasti support), temperatures of 97° F were noted.

As has already been pointed out, gradations in temperature and especially RH are found as one proceeds inland from the seacoast. Somewhat higher temperatures may be recorded, but the decrease in RH is much more obvious even at Dhahran. As one proceeds farther inland, the typical low humidity of the desert is reached. These finer variations in microclimates plus the gradual changes with distances from the sea probably play a definite role in varying the malaria transmission potential throughout the region in question. But our general evaluation of the effects of climate on malaria is based on the general supposition that Ras Tanura data are an adequate measure of the Qatif oasis, and roughly approximate those of al-Hasa. Unfortunately, there are no weather data available in Qatif proper nor in al-Hasa to validate these assumptions. A more detailed discussion of the effects of climate on local malaria transmission and the resulting delineation of spring and fall malaria seasons is given later in this paper.

PART II. EVALUATION OF MALARIA HAZARD

The malaria problem in the Qatif and al-Hasa oases cannot be measured directly. No vital statistics, malaria morbidity rates, or mortality data are available for the general population. As has been pointed out previously, no general census has ever been taken; and any population figures given are crude estimates.

We have used the malaria-morbidity data available from Aramco hospitals and clinics since 1941 as a measure of malaria in the adult population as a whole since these are the only malaria morbidity data available. These data offer a conservative evaluation of the problem since the oasis-dwelling populations (as opposed to employees who live in Company communities or who commute infrequently) are much more frequently exposed to infective mosquito bites. No data are available to measure past malaria morbidity in children other than the precontrol parasite surveys of 1947–1948.

To measure the importance of malaria as a cause of death, we have reviewed death certificates issued on patients expiring in Aramco hospitals including Aramco Saudi Arab employees, their wives and children, as well as all age classes of the general public who have come to the Company's hospitals for medical attention. From a study of causes of death as reported on these death certificates, we have calculated *proportionate mortality rates*. Thus, if deaths in Aramco hospitals are, in general, a good sample of deaths in the general population, these data do give some indication of the relative importance of malaria as a cause of death. These proportionate mortality data are available from 1941 through 1957.

Our third method of ascertaining the importance of malaria in these oases has been the traditional malaria survey. In these surveys, various villages in both oases were selected in 1947 for collecting parasite and spleen data each November. These malaria-survey data taken directly from oasis villages are available from 1947 thru 1957.

MORBIDITY

Before the introduction of malaria-control measures in the fall of 1948, malaria was a most serious problem in Aramco's Saudi Arab labor force. During the spring and fall malaria seasons, large numbers of these employees were affected by malaria, their work efficiency impaired, their sickness and hospitalization rates increased. Key supervisory employees were often lost to the job, and even occasional deaths occurred. Annual morbidity rates throughout

TABLE 7

Precontrol malaria morbidity rates in Saudi Arab employees, Arabian Americal Oil Company, 1941–1947

Year	Number malaria cases*	Midyear employee strength	Morbidity rate per 10,000
1941	380	1,772	2,144.5
1942	280	1,681	1,665.7
1943	540	1,940	2,783.5
1944	688	4,784	1,438.1
1945	838	8,021	1,044.8
1946	802	7,437	1,078.4
1947	2,101	7,846	2,677.8
1941–1947 Average			1,604.1

* Records may include some nonemployees through March, 1947.

TABLE 8

Species of parasite causing malaria infections in Saudi Arab employees, Arabian American Oil Company, 1941–1957

Species	Number	Per cent
Plasmodium vivax	2,849	28.4
Plasmodium falciparum	3,361	33.7
Plasmodium malariae	127	1.3
Mixed infections*	75	0.8
Species undetermined (clinical malaria)	3,585	35.9
Total	9,988	100.0

* Mixed infections were not recorded as such previous to 1947, hence this figure is much smaller than it would be if this distinction had been recorded previously.

the years 1941–1947 varied from slightly over 1,000 cases/10,000 employees in low years to 2,600 and 2,700/10,000 during the more malarious years (see Table 7). From these data, we can infer that the situation among the resident oasis population and among susceptible immigrants was much more serious during the same period.

Only Saudi Arab employees are considered in these statistics. Malaria cases in Palastinian, Pakistani, Indian, or other foreign employees have been eliminated since they might have represented imported rather than true autochthonous cases. Relapses have not been distinguished in our data since we were unable to ascertain which were new infections and which were relapses in these groups. It should also be borne in mind that some of these infections may have been contracted outside the Eastern Province; in malarious areas in the Najd, Hijaz or 'Asir. Again these cannot be distinguished from those contracted in the Eastern Province. We are assuming their number is relatively small and thus will not greatly affect our general conclusions.

Almost 10,000 cases of Saudi Arab-employee malaria were recorded during the 17-year period, 1941 through 1957. The species of *Plasmodium* involved in these cases are shown in Table 8. *Falciparum* infections normally predominated during the seasonal peaks of morbidity in the spring and early summer (April through July) and in the fall (November through December). During the winter (January through March) and late summer (August through October), *vivax* cases were slightly more numerous. Unfortunately, many cases of clinical malaria (especially in the earlier years) obscure a more accurate delimitation of species involved both as far as seasonal differences and annual totals are concerned.

MORTALITY

Since no vital statistics are available for the general oasis population, no comprehensive malaria-mortality rates can be developed for the general population. Mortality rates for the Aramco employee population (adults), however, can be calculated; but the numbers are too small for firm conclusions to be drawn (see Table 9). Based on these meager data, an average annual employee-mortality of 22/100,000 was obtained for the period 1941 through 1947 preceding malaria control measures.

Another measure of the relative importance of malaria as a cause of death in our study area can be obtained from proportionate mortality rates based on analysis of all deaths in all age groups occurring in Aramco hospitals. These data are also outlined in Table 9. As can be seen, an average of slightly over 11 per cent of the deaths occurring in Aramco hospitals throughout this precontrol period (1941 through 1947) was due to malaria. Proportionate malaria mortality rates for the entire period 1941 through 1957 are shown in Fig. 21.

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TABLE 9

Malaria deaths and proportionate malaria mortality rates from analysis of death certificates in ARAMCO hospitals, all age groups except newborns, 1941–1947

Year	Number of malaria deaths			Saudi Arab employee		Deaths from all causes	
	employee	non-employee	total	mid-year strength	mortality rate per 100,000	total deaths	proportionate mortality rate (%)
1941	1		1	1,772	56.4	10	10.0
1942		5	5	1,681	0.0	18	27.8
1943		7	7	1,940	0.0	18	38.9
1944	1	3	4	4,784	20.9	35	11.4
1945	2	7	9	8,021	24.9	81	11.1
1946	2	5	7	7,437	26.9	88	8.0
1947	2	8	10	7,846	25.5	120	8.3
Total	8	35	43	Average	22.1	370	11.6

TABLE 10

Types of malaria causing deaths, ARAMCO hospitals, 1941–1956

Cerebral malaria	50
Blackwater fever	3
Falciparum	15
Vivax	4
Malariae	1
Falciparum-vivax	1
Unspecified	26
	100

In comparing malaria with other specific causes of death in Aramco hospitals, its relative importance before control was paramount. In 1942 and 1943 it ranked *first*; and in 1944, 1945, and 1947 only accidents and pneumonia superseded malaria as ranking causes of death. In the oasis villages, high infant death rates from "fever" were expected during each spring and fall malaria season. Illness, and even death, from malaria were an accepted part of the pattern of oasis life. As might be expected, *falciparum* infections, particularly cerebral malaria, were the most common infections causing fatalities (see Table 10).

MALARIA SURVEYS

In the absence of any more complete morbidity-mortality data on malaria within the province, a general malaria survey in the oasis villages became essential. Hence, spleen and parasite surveys were initiated in the Qatif oasis in 1947 and in al-Hasa in 1948 so that the distribution and intensity of malaria infection could be determined more exactly. Villages with potentially different malaria hazards were selected for this initial survey, some in the most probable malarious areas in the center of date-palm cultivation, others on the margins, and still others, such as al-Khobar, Dammam and Jubail, at some distance from extensively irrigated areas.

In these surveys, samples of children from infancy through 14 years were examined for splenomegaly; and blood films were taken for parasite determination. Only very occasionally would adults allow us to palpate spleens or take blood smears. Spleens were palpated in the upright position because of difficulties in getting cooperation for examining in the more preferred supine position. Hackett's classification (1944) was used in tabulating degrees of spleen enlargement. Unfortunately, several different physicians had to be employed in collecting spleen data which introduced an undesirable variable. Blood films were made using the standard thick-film technique and Giemsa stain. Films were studied on an average of 5 minutes before being declared negative. Surveys were made during the latter part of November and early December at the peak of the fall malaria season.

Survey data were analyzed in the following age groups: 0–11 months, 12–23 months, 2–4 years, 5–9 years, 10–14 years, and 15+ years. Ages had to be estimated since few or none of the children (or their parents) knew their birthdays or could give their true age with any degree of accuracy. In order to make village comparisons more valid, 2–14 year composites were made for each village surveyed. From these data, we were then able to calculate *parasite rate*, *infant parasite rate*, *parasite formula*, *spleen rate*, *aggregate malaria index*, *average spleen*, *average enlarged spleen*, *splenometric index*, and determine a *malaria classification* for the villages surveyed. Survey terminology used here follows the World Health Organization recommendations for standard nomenclature (Covell, Russell and Swellengrebel, 1953).

Such malaria surveys of village children have been made annually in representative villages

TABLE 11

Parasite, spleen, and aggregate malaria indices in 2–14 year age group, 1947–1948

Town	Survey date	Number children examined	Parasite rate (%)	Spleen rate (%)	Aggregate malaria index (%)	Average spleen	Average enlarged spleen	Spleno-metric index	Malaria classification
Qatif Oasis (1947)									
Anik	Nov. 30, 1947	54	98.1	98.1	100.0	2.6	2.6	255.1	Holoendemic
Saihat	Nov. 26, 1947	121	92.6	90.9	99.2	2.4	2.7	245.4	Holoendemic
Qatif	Dec. 9, 1947	52	90.4	98.1	100.0	1.8	1.9	186.4	Holoendemic
Al-Ajam	Dec. 1, 1947	84	77.4	91.7	95.2	2.2	2.4	220.1	Holoendemic
Safwa	Dec. 14, 1947	98	71.4	96.9	99.0	1.8	1.9	184.1	Holoendemic
Jubail	Dec. 16, 1947	115	47.8	87.8	90.4	1.4	1.6	140.5	Holoendemic
Dammam	Nov. 17, 1947	136	39.7	37.5	61.0	0.7	1.8	67.5	Mesoendemic
Al-Khobar	Nov. 19, 1947	50	28.0	10.0	36.0	0.2	1.8	18.0	Hypoendemic
Al-Hasa Oasis (1948)									
Al-Qarah	Nov. 30, 1948	68	100.0	42.6	100.0	1.1	2.5	106.5	Mesoendemic
Al-Jafr	Nov. 29, 1948	29	82.8	48.3	82.8	1.2	2.5	120.8	Mesoendemic
Al-Jishshah	Nov. 29, 1948	42	31.0	26.2	47.6	0.7	2.5	62.5	Mesoendemic
Al-Mubarraz	Nov. 29, 1948	58	15.5	8.6	19.0	0.2	2.2	18.9	Hypoendemic
Hofuf	Nov. 28, 1948	158	13.9	3.8	15.8	0.1	2.5	9.5	Hypoendemic

in the Qatif oasis since 1947 and in the al-Hasa oasis since 1948. Certain selected villages, in typical oasis locations, have been surveyed year after year in late November; normally the peak month of the fall malaria season. These data have been used to describe the hyperendemic malaria of the typical oasis village and have been most useful in evaluating the results of residual sprays in malaria control. In later years, they provide excellent malariometric evidence for development of DDT resistance in *Anopheles stephensi* and for resumption of effective malaria control when dieldrin was substituted for DDT.

The results of the first surveys (Qatif, 1947; al-Hasa, 1948), made before introduction of any control measures, are summarized in Table 11. The variations in parasite rate show close correlation with the geographical position of the village in regard to irrigated date-palm gardens. Villages completely surrounded by these potential anopheline breeding areas (see Figs. 1 and 2) show the highest parasite rates, viz., al-Qarah, 100%; 'Anik, 98%; Saihat, 93%; Qatif, 90%; al-Jafr, 83%; and al-Ajam, 77%. Those less closely associated with the palm belt or located on its margins show lesser degrees of infection, viz., Jubail, 48%; Dammam, 40%; al-Jishshah, 31%; al-Khobar, 28%; al-Mubarraz, 16%; and Hofuf, 14%.

The very high prevalence of malaria in these true oasis villages is emphasized by these parasite rates. In general, the spleen data corroborate this evidence. The parasite rate of the 2-to-14-year group (average 85% in the Qatif oasis proper) is the benchmark from which success of malaria control measures in succeeding years was plotted. This same 2-to-14-year age group is used in comparing malariometric data throughout pre- and post control years.

Analysis of Survey Data by Age Groups

A comparison of survey data by age groups from the five garden villages (the most highly malarious) studied in the Qatif oasis shows an interesting picture of typically hyperendemic malaria for the oasis proper (see Table 12). In both of our oases, the precontrol infant parasite rate (transmission index) was 100 per cent; indicating total infection of the infant population in its first year of life as well as the great general risk of malarial infection in these oases in all age groups. Parasite rates are seen to decline with increase in age. A reverse relationship is seen when age-specific spleen rates are studied. This is a reflection of normal im-

munity development in an oasis population exposed from birth to repeated malarial infection. The infants and younger children show the typically high gametocyte rates associated with hyperendemic malaria. Older children show an expected decline in gametocyte rate with increasing age.

TABLE 12

Parasite and spleen rates by age groups, Qatif Oasis, 1947

Age group	Children examined	Parasite rate (%)	Gametocyte rate (%)	Spleen rate (%)
0–11 months	11	100	27	64
12–23 months	21	95	24	67
2–9 years	217	89	14	96
10–14 years	192	81	13	93
15 years and older	14	79	7	100
Total	455	86	14	93
2–14-year composite	409	85	13	94

Species of Plasmodium. An analysis of the species of *Plasmodium* contributing to different degrees of parasitemia (*parasite formula*) is shown in Table 13. The percentages are based on total number of children examined in each of the villages indicated. The general composite averages must be carefully weighed because of the unusual predominance of *malariae* infections in 'Anik and in al-Jafr.

Falciparum infections usually predominate in hyperendemic situations. This is confirmed by our Qatif data. *Malariae*, as a species, is known for the "patchiness" of its distribution. Certainly the unusual predominance of *malariae* in al-Jafr (67% of positives) and 'Anik (42% of positives) is a good example of this unusual localized distribution.

TABLE 13

Distribution of parasite species (parasite formulas) in 2–14 year age group

Town	Survey date	Number children examined	Parasite rate (%)	Percent falciparium positive	Percent vivax positive	Percent malariae positive	Percent unidentified	Percent mixed infections
Qatif Oasis								
'Anik	Nov. 30, 1947	54	98.1	33.3	13.0	40.7		11.1
Saihat	Nov. 26, 1947	121	92.6	52.9	19.8	9.1		10.7
Qatif	Dec. 9, 1947	52	90.4	32.7	34.6	17.3	1.9	3.8
Al-Ajam	Dec. 1, 1947	84	77.4	26.2	40.5	2.4	4.8	3.6
Safwa	Dec. 14, 1947	98	71.4	24.5	29.6	14.3		3.1
Jubail	Dec. 16, 1947	115	47.8	9.6	27.8	9.6		0.9
Dammam	Nov. 17, 1947	136	39.7	29.4	6.6	2.9		0.7
Al-Khobar	Nov. 19, 1947	50	28.0		28.0			
Total		710	66.2	27.6	23.5	10.3	0.7	4.1
Composite of five garden towns excluding Dammam, Jubail, and Al-Khobar		409	84.8	35.5	27.4	14.2	1.2	6.6
Al-Hasa Oasis								
Al-Qarah	Nov. 30, 1948	68	100.0	39.7	30.9	26.5		2.9
Al-Jafr	Nov. 29, 1948	29	82.8	10.3		55.2	13.8	3.4
Al-Jishshah	Nov. 29, 1948	42	31.0	16.7	14.3			
Al-Mubarraz	Nov. 29, 1948	58	15.5	12.1		3.4		
Hofuf	Nov. 28, 1948	158	13.9	12.7	0.6	0.6		
Total		355	38.3	18.0	6.2	12.1	1.1	0.8
Composite of three garden towns excluding Hofuf and Al-Mubarraz		139	75.5	26.6	15.1	28.8	2.9	2.2

TABLE 14

Species prevalence by age groups, Qatif Oasis, 1947

Age group	Number parasite-positive	Falciparum (%)	Vivax (%)	Malariae (%)	Unidentified (%)	Mixed (%)
0–11 mos.	11	64		27		9
12–23 mos.	20	55	20	5		20
2–9 yrs.	192	40	32	17	1	10
10–14 yrs.	155	44	33	16	2	5
15+ years	11	36	46	9	9	
Total	389	43	31	16	2	8
2–14-year composite	347	42	32	17	1	8

TABLE 15

Age-specific splenomegaly, Qatif Oasis, 1947

Age group	Children examined	Spleen rate (%)	Average spleen	Average enlarged spleen	Splenometric index
0–11 months	11	63.6	1.5	2.4	152.6
12–24 months	21	66.7	1.9	2.8	186.8
2–9 years	217	95.9	2.3	2.4	230.2
10–14 years	192	92.7	2.1	2.2	203.9
15+ years	14	100.0	2.4	2.4	240.0
Totals	455	92.5	2.2	2.3	212.8
2–14-year composite	409	94.4	2.2	2.3	217.1

The predominance of *falciparum* infections over those of *vivax* and *malariae* is shown in Table 14 where species percentages are based on the total number of positive smears. These data are taken from typical garden villages in the Qatif area excluding al-Khobar, Dammam, and Jubail.

The relatively large percentage of mixed infections further emphasizes the intensity of malarial attack in the oasis villages; particularly in the younger children.

Splenomegaly. Hyperendemic malaria, by definition, occurs when the spleen rate in children 2 to 9 years of age is constantly over 50 per cent. In most cases in our more maiarious villages, it approached more nearly 100 per cent. Our precontrol splenomegaly data for the various villages are shown in Table 11; an age-specific analysis in Table 15.

TABLE 16

Correlation of parasitemia with splenomegaly, Qatif Oasis, 1947

Spleen class	Children examined	Per cent of total examined	Parasite positive (No.)	Parasite positive (%)
0	167	23.5	65	38.9
1	130	18.3	76	58.5
2	236	33.2	179	75.8
3	159	22.4	133	83.6
4	18	2.5	17	94.4
5	0			
Totals	710	100.0	470	66.2

In general, our spleen data follow the same relative alignment as do our parasite data insofar as measuring village malariousness is concerned. The spleen rate, size of average spleen and splenometric index all show a general increase with age. This is probably indicative of parallel immunity development characteristic of hyperendemic populations.

A very pronounced correlation between increase in parasitemia and increase in degree of splenomegaly is shown in Table 16. Data were gathered from highly malarious villages within the garden area as well as from nearby less malarious towns such as Dammam, al-Khobar, and Jubail. With this high correlation between degree of spleen enlargement and positive parasitemia, we conclude that spleen surveys alone would be useful rough tools in determining malarial intensity in this area. However, spleen surveys elsewhere in the Kingdom may be less useful because of the occurrence of schistosomiasis in the Najd, Hijaz, and 'Asir. Spleen enlargement from this source may obscure the relative importance of splenomegaly as a measure of malaria in these other areas. No evidence of vector snails or local transmission of schistosomiasis is available for either the Qatif or al-Hasa oases although infected immigrants are now commonly found residing in the Eastern Province (Tarizzo, 1957).

From all these various data, morbidity, mortality, and village surveys, there is no doubt that malaria can be a most serious disease prob-

lem in oases of the Eastern Province. Since the bulk of Aramco employees come from these oases, it follows that malaria is a most serious health problem for Aramco. This same potential problem is faced by other industrial organizations operating in the area, and is especially important in future agricultural development of the region as well.

PART III. BIONOMICS OF ANOPHELINE VECTORS

Fourteen different anophelines have been reported from Saudi Arabia (see Table 17), but of these, only six have been reported from the Eastern Province. These species are *Anopheles stephensi, fluviatilis, sergenti, pulcherrimus, multicolor* and *coustani* var. *tenebrosus*.

The earliest collections of anophelines made in the Eastern Province are probably those of Hopkins (recorded by Leeson, 1948) who made a malaria survey in 1943–44. Identifications of *A. stephensi, fluviatilis, sergenti, pulcherrimus, multicolor* and *coustani* were made from this material. A few larvae of *A. hyrcanus* were also reported, but these have since been determined as *coustani*, probably the variety *tenebrosus*, by Mattingly and Knight (1956). Leeson's (1948) reference to *cinereus* has also been determined as *multicolor* by Mattingly and Knight. Giles (1906) had previously reported *stephensi* from Bahrain Island.

Of these recorded species, *stephensi* is the most important vector along the Persian Gulf, and the bulk of the present discussion will be devoted to the bionomics of this species in relation to our local malaria problem.

SPECIES OF *ANOPHELES* IN THE EASTERN PROVINCE

Anopheles fluviatilis is second in abundance and probably of minor importance as a secondary vector although no exact information on its local role in transmission is presently available. It is one of the most important vectors (with *culicifacies*) in rural areas of northern and peninsular India.

Anopheles sergenti is found in Qatif and al-

TABLE 17

Distribution of Anopheline Mosquitoes in Various Provinces of Saudi Arabia and in Neighboring Countries

SPECIES	Hijaz	'Asir	Nejd	Eastern Province	Bahrein Island	Trucial Coast	Dhofar Oman Muscat	Aden Hadhramaut	Yemen	Egypt (Sinai)	Jordan	Southern Iraq
1. *Anopheles (Anopheles) algeriensis* Theobald											X	X
2. *Anopheles (Myzomyia) apoci* Marsh												X
3. *Anopheles (Myzomyia) cinereus* Theobald		X						X	X			
4. *Anopheles (Anopheles) claviger* (Meigen)											X	
5. *Anopheles (Anopheles) coustani coustani* Laveran		X										
6. *Anopheles (Anopheles) coustani tenebrosus* Dönitz				X			X					
7. *Anopheles (Myzomyia) culicifacies culicifacies* Giles					X	X	X					
8. *Anopheles (Myzomyia) culicifacies adenensis* Christophers						X		X	X			
9. *Anopheles (Myzomyia) demeilloni demeilloni* Evans								X	X			
10. *Anopheles (Myzomyia) dthali* Patton	X						X	X	X	X	X	X
11. *Anopheles (Myzomyia) fluviatilis* James				X	X		X					X
12. *Anopheles (Myzomyia) gambiae* Giles	X	X						X	X			
13. *Anopheles (Myzomyia) hispaniola* Theobald											X	
14. *Anopheles (Anopheles) hyrcanus hyrcanus* (Pallas)											X	X
15. *Anopheles (Anopheles) marteri* Senevet and Prunelle											X	
16. *Anopheles (Myzomyia) multicolor* Cambouliu	X		X	X		X				X	X	X
17. *Anopheles (Myzomyia) pharoensis* Theobald	X								X	X		
18. *Anopheles (Myzomyia) pretoriensis* (Theobald)								X	X			
19. *Anopheles (Myzomyia) pulcherrimus* Theobald				X	X							X
20. *Anopheles (Myzomyia) rhodesiensis rupicolus* Lewis	X							X	X	X	X	
21. *Anopheles (Anopheles) sacharovi* Favre											X	X
22. *Anopheles (Myzomyia) sergenti* (Theobald)	X		X	X	X			X	X	X	X	X
23. *Anopheles (Myzomyia) stephensi* Liston			X	X	X	X	X					X
24. *Anopheles (Myzomyia) superpictus* Grassi			X							X	X	X
25. *Anopheles (Myzomyia) turkhudi* Liston	X							X	X	X		

Hasa oases occasionally, but its numbers are very small and of no significance in comparison with the overwhelming preponderance of *stephensi*. *Anopheles sergenti* was the only anopheline found by the writer in Yabrin; and the species is known to be a prominent vector in the smaller interior oases of the Najd and Hijaz, in Jordan, Israel and the Egyptian oases.

Anopheles multicolor is also relatively rare in the Eastern Province and has been collected by the writer at al-Kharj in the Najd. It is widely distributed throughout desert regions in the Middle East and North Africa. It is of doubtful importance as a malaria vector but has been suspect in some areas in Egypt on epidemiological evidence.

Anopheles pulcherrimus is also widely distributed in this part of the world but is generally regarded as of little or no importance in malaria transmission. This species is known to withstand high temperatures and to migrate great distances (15 miles) while being carried by winds (Horsfall, 1955). This explains the occasional occurrence of *pulcherrimus* in Dhahran when the nearest breeding areas are at least 5 to 7 miles distant.

Anopheles coustani var. *tenebrosus* is a conspicuous large black anopheline also occasionally found in both Qatif and al-Hasa oases, but it is of no importance as a malaria vector.

Further intensive mosquito collecting in the Eastern Province may show the occurrence of *A. culicifacies* which has been reported from neighboring Bahrain, the Trucial Coast, and Oman. Its subspecies, *adenensis*, is also recorded from the Trucial Coast. *Anopheles dthali* is widely distributed and has been recorded from adjacent areas. More collecting is likely to disclose it here as well. Table 17 summarizes the recorded distribution of anophelines in the different provinces of Saudi Arabia and in neighboring countries. Sources used in compiling the table include Mattingly and Knight (1956), Abdel-Malek (1956), Leeson (1948), Leeson, Lumsden, Yofe and Macan (1950), Pringle (1954), Pringle and Garrett-Jones (1957), and Zahar and Dabbah (1957).

Anopheles stephensi, the local vector

This species is the most important vector throughout the Persian Gulf littoral and in coastal and urban India. In addition to the Qatif and al-Hasa oases, we have collected *stephensi* from Sarar and from the al-Kharj district in the Najd. The species ranges from eastern Saudi Arabia and southern Iraq eastward and southward across India to Burma and China. Sonthinand (1952) extended the known distribution to Thailand. A variety, *A. stephensi mysorensis*, described by Sweet and Rao (1937), has been thus far known only from India and Pakistan (Husain and Talibi, 1956). But recent measurements of *stephensi* eggs collected from the Qatif oasis and measured by Dr. R. L. Peffly, Aramco entomologist, indicate the variety *mysorensis* may also occur here in eastern Saudi Arabia. Russell and Mohan (1941) have found no significant differences between the type form and its variety insofar as experimental malaria infections are concerned. Krishnan (1954) has summarized much of our knowledge of this species in a review of malaria vectors of India.

Afridi and Majid (1938) found *stephensi* to be the only Bahrain anopheline infected with malaria parasites. In their studies, 1,142 specimens were collected for dissection from various localities on the island (May–June, 1938). Eight positive gut infections (oocyst rate, 0.7%) were found. In 186 specimens from garden huts (barastis), 2.7 per cent were found to have positive gut infections. Certainly with the heavier parasite rates in the Qatif oasis, our mosquito infections must have been correspondingly higher before control although no dissections were made locally. Covell (1944) refers to an infectivity rate of 9.3 per cent reported during a malaria outbreak in Lucknow, India. This evidence together with similar evidence from other workers in India leaves no doubt that *stephensi* is a major malaria vector. This coupled with its overwhelming predominance in numbers in Qatif and al-Hasa makes it the chief target species in any mosquito-malaria control schemes in these oases.

Day Resting Places

Favored diurnal resting places for anophelines are ideally found in the palm-thatch, windowless barastis of the oases and in the thick-walled masonry or adobe houses in the larger villages. Since sunlight is intense outside and the hot dry air of early summer is often gusty and dust-filled, windows are few, small, or absent in most oasis dwellings. Thus the most important requirement, relative darkness, is well fulfilled, especially in barastis. The microclimates in dwellings and stables, concentrated in oasis

TABLE 18

Anopheline population species analysis based on combined shelter collections, Qatif Oasis, 1947–1949

Mosquito species	Adult collections from daytime resting shelters						
	Males		Females		Total	Anopheline (%)	Total mosquitoes (%)
	No.	%	No.	%			
Anopheles stephensi	2,280	28.5	5,709	71.5	7,989	90.6	90.0
*Anopheles fluviatilis**	198	31.2	437	68.8	635	7.2	7.2
Anopheles pulcherrimus			193	100.0	193	2.2	2.2
Anopheles coustani var. *tenebrosus*			5	100.0	5	0.06	0.06
Subtotal							
Anopheles species	2,478	28.1	6,344	71.9	8,822	100.0	99.4
Culex and *Aedes* species					51		0.6
Totals					8,873		100.0

* Some *A. sergenti* or *multicolor* may be included in these figures since identification of rubbed specimens is often difficult.

villages, are thus ideal for attracting vector mosquitoes during the day. Caves, culverts, hollow trees, and dense vegetation other than cultivated crops are not generally available for shelter. Hence artificial shelters, such as houses and stables, are concentration points for daytime resting. This is, of course, most important for success in residual-spray control programs.

Anopheles stephensi is a domestic species and is readily attracted to these man-made shelters. Enormous numbers of adults can be found during the day resting in houses and stables. The darker palm-thatch shelters seem to be preferred. As many as 500 to 600 engorged *stephensi* females have been taken in 12 to 15 square feet of wall surface in highly favored resting places in the Qatif area.

A compilation of all such shelter collections (Table 18) showed *stephensi* to be the predominant house-resting anopheline (90.6%) with *fluviatilis* ranking a poor second (7.2%). *Pulcherrimus* was occasionally found, but *coustani* var. *tenebrosus* was only rarely encountered in house collections. Culicines in general made up only a very minor part of the total mosquitoes collected from day shelters.

New Jersey Light Trap Collections

The New Jersey light trap (battery operated) is well known as a mechanical means of studying mosquito populations. Traps were run in the Qatif oasis about twice each month throughout the period October 9, 1948 through July 2, 1950. During this period some 1,613 anophelines were collected, 79.3% of which were *stephensi*, 16.0% *fluviatilis*, and 4.7% *pulcherrimus*. Although the catches were somewhat erratic (perhaps influenced by winds, moonlight, and other variables), the largest single catches of anophelines occurred in the fall (October 11, 1948 and November 8, 1949) during the height of the malaria transmission season. Variations were too great to detect finer definition in seasonal patterns of anopheline density. The general seasonal trend, however, reflected the anopheline-density curve shown in Fig. 13, even though our residual-spray program began shortly after light-trap studies were inaugurated.

Anophelines collected in houses and in light traps in the same vicinity are compared in Table 19. From this, we can conclude that the New Jersey light trap may have a place in crude sampling for anopheline species in this area.

Feeding

Stephensi feeds avidly on man, but apparently does not prefer man to other animal blood sources. Afridi, Singh, and Singh (1939), in studies conducted in Delhi, reported only 1.4 per cent of 360 specimens examined to have fed on human blood. Their observations indicated that cattle were preferred. Roy, Chandra, and Siddons (1938), in precipitin tests on *stephensi* collected in a Calcutta bedroom, found only 3.4 per cent with human blood, the re-

TABLE 19

Shelter collections vs. adjacent light traps in sampling anopheline populations, Qatif Oasis

Anopheles species	Day resting places		Light trap	
	No.	%	No.	%
A. stephensi	1,938	96.6	1,279	79.3
A. fluviatilis	47	2.3	259	16.0
A. pulcherrimus	23	1.1	75	4.7
Total	2,008	100.0	1,613	100.0

TABLE 20

Stephensi blood meal sources from precipitin tests, Bahrain Island, 1948

Host	Number	Per cent
Human	5	3.3
Equine (presumably donkey)	49	32.0
Bovine (cattle)	39	25.5
Sheep	26	17.0
Avian	4	2.6
Negative	23	15.0
Unsatisfactory	7	4.6
Total	153	100.0

mainder had fed on ruminants, presumably on cattle stabled nearby. A small number of *stephensi* (collected by Mr. Henry Chubb in 1948 on Bahrain Island) sent to the United States Public Health Service Communicable Disease Center, Atlanta, Georgia, for precipitin testing showed comparable results (see Table 20) in relative utilization of humans as a blood source (Pratt, 1949, personal communication). In all these examples, the numbers are too small to make broad generalizations; but results do indicate that man is apparently not a preferred local source of blood meals for *stephensi* if other sources are readily available.

Feeding begins immediately after sundown. No evidence of daytime feeding has been noted; even in dark huts while making collections for anopheline density studies. Chaudhuri (see Strickland, Roy and Chaudhuri, 1936) found feeding most active just before midnight when temperature was 80.6 to 91.4° F (27 to 33° C) and relative humidity was 90 per cent.

Flight Range

The frequency and dispersal of breeding places in the Qatif and al-Hasa oases makes maximum flight range of *stephensi* a question of academic interest only. Oasis villages are closely surrounded by irrigated agricultural land, and favored breeding places may be found almost everywhere. Almost all oasis villages are thus located within a fraction of a mile from potential breeding sites. Only the centers of the larger towns may be beyond the 1.5-mile effective *stephensi* flight range reported by Afridi and Majid (1938) on Bahrain Island. Covell (1944) points out that the extreme localization of malaria in urban areas of India would seem to indicate an effective flight range not in excess of 0.5 mile. We have no additional observations on flight range to add to the above references.

Breeding Places

Malaria in the Qatif and al-Hasa oases is largely *man-made malaria*; the great majority of anopheline breeding places being the direct result of the inefficient irrigation and drainage systems which have been constructed in the past. Almost all the present anopheline breeding areas can be attributed to this source.

Among the important types of breeding places now existing are the following:

1) *Drainage ditches*, forming a vast network throughout the oases, are used to draw off excess irrigation water. At the heads of these drains, seepage water accumulates in shallow collections, gradually increases in amount, and joins similar feeder ditches in a linked system. Finally, drains the size of small rivers carry excess water to the sea (Qatif area) or to seasonal lakes or swamps at the edge of the palm belt (al-Hasa). At the heads of these drains, water flow is sluggish and intermittent stagnation occurs.

These drainage ditches are usually clogged with vegetation such as grass, rushes, and algal mats (Fig. 10). From the smallest to the largest, they form ideal protected living places for anopheline larvae. The larger drains may be several feet deep and have a swift flow. Here anophelines can still be found (in smaller numbers) in protected spots along the margins where emergent vegetation and algal mats offer protection both from the effects of the strong current and small fish which may be present. In general,

FIG. 7. Large spring at Safwa (Qatif oasis)
(Photo by E. E. Seal)

the smaller, slow-moving, semi-stagnant, vegetation-clogged drains form the most important *stephensi* breeding places in the oases.

2) *Irrigation canals*, as such, are of much less importance in contributing to mosquito breeding. Usually the flow is swift and often intermittent while different sections of the garden are being watered. The larger canals with vegetation along the margins do breed some anophelines, but not nearly to the extent of their drainage counterparts (Fig. 8).

3) *Seepage areas* often form along the margins of poorly constructed irrigation canals. Water seeps thru the banks and collects in low spots to form grassy pools ideal for anophelines. These are usually free of fish, and larval populations in favored seepages may be very high.

4) *Ponds* are occasionally formed when heavier seepage drains into larger basins adjacent to irrigation canals. Larvae are especially numerous in their grassy margins. If the pond is protected from heavy wave action, some larvae may be taken throughout the entire open-water surface of these shallow water accumulations (Fig. 4).

5) *Swamps* are formed where drainage collects in low-lying areas at the margins of the palm gardens. These may vary in size from small marshy areas to swamps acres in extent. In most cases, grasses, rushes, and other protective vegetation offer excellent mosquito breeding places. *A. stephensi* may be found in these locations, but the larger swamps seem more favored by *pulcherrimus* than by *stephensi*.

6) *Temporary lakes*, sometimes of very great extent, form from accumulated garden drainage in low areas during the winter months. These are normally dry in midsummer when water usage is heavy and evaporation rates are high. Heavy wave action prevents anopheline breeding except for certain portions which may have

FIG. 8. Irrigation canal at Safwa (Qatif oasis)
(Photo by E. E. Seal)

protective vegetation along the shoreline. Most of these large seasonal lakes have clean shorelines and hence are of no importance in contributing to the vector population.

7) *Shallow wells*, especially if abandoned or used infrequently, form excellent breeding places for local anophelines. Usually emergent vegetation and algal mats furnish ideal protected areas around the margins of wells that are still in partial use. Abandoned wells may be completely grown over with vegetation. Unless fish are introduced into these wells as a control measure, *stephensi* larval populations are usually heavy (Fig. 11).

8) *Artesian wells* have been drilled in many parts of the Qatif oasis, fewer are found in al-Hasa. When properly constructed and equipped with shut-off valves, they offer no hazard in themselves. Unfortunately, many of them are uncapped and flow continuously (Fig. 9). Others have been poorly constructed, leak around the casing, or the valves do not shut off properly. In these cases, waste water accumulates around the well; and ideal *stephensi* breeding areas result. On some occasions, the water flow is too small to make gardening profitable. The gardens are then abandoned, but the water continues to flow; again forming ideal *stephensi* breeding places.

9) *Borrow pits* (especially in the al-Hasa area where mud brick is used in construction) are usually filled with water during fall, winter, and early spring months. They may or may not have vegetation in them, depending upon current use or age. These pits furnish ideal breeding sites for *stephensi*, and extremely

FIG. 9. Artesian well without control valve (Qatif oasis)
(Photo by E. E. Seal)

heavy larval populations may be found in them.

10) *Small shallow puddles*, entirely free of macroscopic vegetation, may also be utilized by *stephensi*. They may form from accumulations of waste water, spillage from buckets used to bring water from deep wells, or other sources. *Stephensi* is often found in very large numbers in these shallow surface-water accumulations.

11) *The ground-water table*, especially during the cooler months of the year, may rise to a level where shallow surface-water accumulations become common in low-lying, water-logged areas. This rise in ground-water level results from excess irrigation, water wastage, poor drainage, and lowered evaporation rates during the cooler weather. The end result is a wide variety, both in size and type, of additional, temporary, surface-water collections (Fig. 12). In many cases, anophelines are found in large numbers in the more favored types of breeding places thus formed.

12) *Artificial containers* are of no importance in furnishing breeding places for *stephensi* in our oases, even though this species utilizes such containers in Indian urban centers such as Calcutta and Bombay. In these cities, according to Covell (1944) and others, *stephensi* may be found breeding in overhead cisterns, tanks, tubs, roof gutters, discarded tires, and receptacles of all kinds. In our early mosquito surveys in Dammam and al-Khobar, many collections of water in such artificial containers were examined, but in no case were anophelines found. Roy (1931) feels that tanks and cisterns are used primarily to tide the species over dry seasons, and that temporary pools formed during the rainy season (in Calcutta) are the true habitat. In our oases, surface-water breeding places are found throughout the year; and there is no need to utilize artificial containers at any season.

13) *Rice fields* are apparently of no importance in *stephensi* breeding. None was collected from rice fields in our surveys, although some were found in the drains from rice fields. Russell and Rao (1940), after intensive surveys of rice

FIG. 10. Typical drainage ditch (Qatif oasis)
(Photo by E. E. Seal)

fields in southeastern Madras, collected ten species of anophelines, but *stephensi* was invariably absent although found in wells in the area. The subject deserves more investigation; but from present knowledge, it appears that rice cultivation in our oases does not appreciably increase our malaria problem.

A. stephensi larvae show a remarkably high tolerance to salinity, being frequently found locally in puddles having a thick crust of salt around their margins. Chalam (1926) reported *stephensi* breeding under natural conditions in water having a saline concentration three times that of sea water. Bana (1943) found *stephensi* breeding in salt pans in Bombay in September and October when these pans are used for raising fish. The water was diluted 50 per cent by rain water. Larvae were also found in tanks and drums filled with sea water partially diluted by rain, and even in water (specific gravity of 1.030) equivalent in salinity to that of sea water. Afridi and Majid (1938) reported the upper limit of salinity in which they found *stephensi* on Bahrain to be 2,750 parts of chlorine per 100,000 (sea water is usually about 2,000 parts chlorine per 100,000). From these observations, it seems obvious that *stephensi* may breed in brackish waters of widely varying salinity, and that high salt content is no deterrent.

Normally, *stephensi* is found in clear, clean water, but occasionally we have taken it in polluted waters in drains. Roy (1931) has also reported *stephensi* from open drains with foul water and at times in sewage-contaminated waters in Calcutta.

From the above discussion, it can be seen that *stephensi* utilizes a wide variety of ground-

FIG. 11. Abandoned well near al-Ajam (Qatif oasis)
(Photo by E. E. Seal)

water accumulations for breeding sites in our oases. These vary in size from hoofprints to protected margins of large lakes or large swamps, from puddles free of vegetation to grass-choked drains and seepage areas, from stagnant water to protected margins and eddies in swiftly flowing drainage ditches, from sweet water to highly brackish water, and from clean to highly polluted waters. The larger swamps may be less frequently utilized by *stephensi* than by other anophelines; but the only breeding sites totally free from *stephensi* seem to be the large, wave-swept, temporary lakes and the small artificial containers. In almost all other accumulations of ground water, *stephensi* may be found.

LIFE CYCLE OF *ANOPHELES STEPHENSI*

Eggs are laid at night in a wide variety of breeding places already described. Apparently they are very resistant to desiccation, Chalam (1927) reporting egg survival for 12 days after they were allowed to dry on mud at room temperatures. When eggs were floated off into water, some hatched although none survived a 15-day drying period. Roy (1931) found *stephensi* eggs hatching 5 days after drying at 51.8° F, but none hatched 7 days after such drying. Lal (1953) determined the thermal death point (1-hour exposure time) for *stephensi* eggs to be 122.9° F. This means that intermittent drying of irrigation channels and drainage ditches as a local control measure would not be totally effective in eliminating the egg stage.

In further studies in Lahore, Lal did not find larvae in water hotter than 113° F, and only occasionally were larvae found in water as warm as 109.4° F. Larvae were active at these higher temperatures, but pupation did not take place. The writer has collected local *stephensi* larvae in large numbers in shallow wells at 90° F and from roadside pools up to 93° F. Lal found thermal death points for various larval instars were intermediate between those for eggs (122.9° F) and pupae (106.7° F). From

FIG. 12. Water-logged areas near 'Anik (Qatif oasis)
(Photo by E. E. Seal)

these data, it is obvious that all aquatic stages have considerable resistance to high temperatures in their breeding sites.

Optimum temperature for *stephensi* development was determined by Lal to be 89.6° F. At this temperature, the shortest life cycle with highest percentage of egg hatch and successful pupation occurred. Complete development from egg to adult averaged 8.1 days at this temperature, some individuals emerging in less than a week. The general range of favorable developmental temperatures was set at 77 to 93.2° F. In India, Strickland, Roy, and Chaudhuri (1936) found *stephensi* to be very prevalent when temperatures were between 77 and 89° F and relative humidity was about 85 per cent.

Lal found fourth-stage larvae more resistant to low temperatures than any other stage. In Lahore, *stephensi* is reported to pass the winter in a state of retarded growth since the colder temperatures during December through February (51.8–64.4° F) restrict larval development but do not destroy the larval population.

In our oases, winter temperatures are milder. Average daily temperatures below 60° F are relatively rare, and mean weekly temperatures are usually above this point (see Table 6). In addition, many of our artesian wells and springs are warm and thus provide more favorable temperatures for breeding in colder months. With our mild winters, adults and larvae of *stephensi* can be found in our oases any month of the year—although the population density varies markedly with seasonal cycles of optimal temperature and relative humidity.

Anopheline Density in Relation to Temperature and Relative Humidity

Dakshinamurty and Sharma (1951a) studied the temperature and humidity preferences of *stephensi* in the laboratory. When temperature gradients of 68° to 77° F and 77° to 86° F were offered (with constant saturation deficiency and light), a definite preference was shown at 77° F. This choice was said to be highly significant statistically. In similar studies by these investigators (1951b) on humidity preferences (with constant temperatures and light), the following results were recorded:

1) at temperatures above 86° F, *stephensi* preferred higher humidities to lower.
2) at temperatures below 86° F, *stephensi* showed no preferences when 20 to 60%, 40 to 60%, and 60 to 80% RH were offered. When 80 to 100% RH were offered, they preferred 80%.

Mayne (1930) has studied the survival of *stephensi* and *culicifacies* adults kept at different temperatures and humidities. His results are summarized as follows:

Species	Temperature range (°F)	RH (%)	Days survival
A. stephensi	80–87	40–42	1
	85–94	55–58	7–22
	85–86	80–88	7–32
A. culicifacies	85–86	80–88	7–21
	80–93	40–46	1–4

Pal (1943), in more extensive experiments utilizing *Anopheles culicifacies*, obtained the following data showing the effects of variations of high temperatures with different RH:

Temperature (°F)	RH (%)	Days survival
65	80	33
77	20	14
77	60	28
86	20	6
86	60	18
95	20	4
95	80	10
104	20–100	19 (hours)
122	20	5 (minutes)

Although Sinton and Shute (1938) indicate that *stephensi* may outlive *culicifacies* at lower humidities, the data listed above probably apply quite closely to *stephensi*. The dramatic effect of low RH in reducing longevity is well illustrated by these data. It is evident that an increase in humidity can compensate for an increase in temperature (within limits), but adequate compensation for extremely high temperatures by increased humidity is impossible. This becomes a matter of great importance in the local epidemiology of malaria in our oases.

Adult anophelines are usually very susceptible to high temperatures. Short exposures to temperatures in the range 104° to 113° F may prove quickly fatal (Muirhead-Thomson, 1951). Certain microclimates thus become important in tiding over adults through these periods of unfavorably high temperatures.

A most interesting reaction to high temperatures and low RH can be observed in the local, native barastis which furnish daytime resting places for adult *stephensi*. In the spring and fall, when temperatures and humidities are most favorable, adults may be found resting on the ceiling and upper portions of the walls. As maximum summer temperatures approach, accompanied by lower RH, there is a definite vertical shift downward toward the floor levels. Thus, on the hottest, driest days anophelines are not only rare but are almost always found on the earthen floor itself or resting a few inches above it. During these observations, room temperatures reached 104 to 106°; and even at floor level, temperatures of 100° F were recorded. In many cases, the mosquitoes would be clustered around the "sweating" earthen water jars when these were found in barastis. This downward dispersal is an obvious selection of cooler, more humid resting places to survive the most critical temperature period in their seasonal life cycle.

Another example of selection of most favorable microclimates under extremes of temperature was first noted in making adult mosquito collections in a barasti near al-Khobar in July and August, 1948. On several different days, barasti room temperatures were recorded at 103 to 106° F. Maximum outdoor temperatures during this same period at Ras Tanura reached 116° F. Only a few adult *fluviatilis* were found in the barasti, but all of them were concentrated in small crevices in a rough stone wall where,

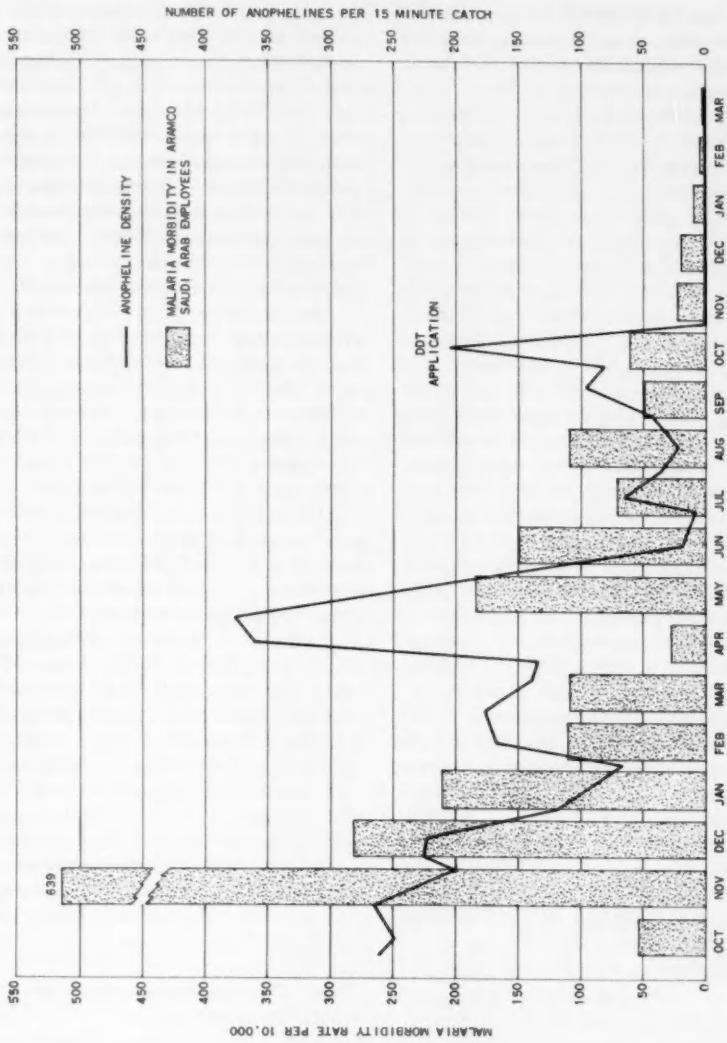
NUMBER OF ANOPHELINES PER 15 MINUTE CATCH
MALARIA MORBIDITY RATE PER 10,000
ANOPHELINE DENSITY
MALARIA MORBIDITY IN ARAMCO SAUDI ARAB EMPLOYEES
DDT APPLICATION
639
OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC JAN FEB MAR
0 50 100 150 200 250 300 350 400 450 500 550

FIG. 13. Seasonal malaria incidence in relation to fluctuating anopheline densities, Qatif oasis, 1947–1949

by contrast, the microclimate temperature was 97° F. Presumably, more favorable humidity conditions also existed in this microhabitat, but these were not measured.

This direct relationship between fluctuating anopheline densities and seasonal malaria morbidity is shown in Fig. 13. Anopheline counts shown in the figure were made in a favored, daytime, resting place in a Saihat barasti at the edge of a palm garden. A 15-minute collection by aspirator, made twice each month by the writer, gave the data used in plotting the anopheline-density curve. With very minor exceptions, almost all the anophelines collected were *A. stephensi* (99.5%). Even though this represents adult-mosquito collections from a single resting place, the general pattern shown here was repeated in several other selected barastis used as collection sites in various parts of the Qatif oasis. Thus, we feel that the curve shown is generally indicative of the seasonal fluctuation in anopheline population density.

The peak count of 371 made on May 1, 1948 represents only the maximum speed of the collector in using an aspirator since only a small portion of the room was sampled. The previous fall peak may have been equally as high or higher if the collector had been equally adept at the beginning of the shelter-collection study. When populations were at a minimum in July and August, the whole room would be covered in a 15-minute search, usually at ground level, in order to find any mosquitoes at all.

In general, weather conditions over the period covered by the chart were close to the averages shown in Table 6. However, during the 1947 fall peak, October, the latter part of November and most of December were somewhat more humid and November temperatures somewhat warmer than the average (see Table 24). March and early April, 1948, were somewhat cooler, and this might help explain the lag and sudden spurt in attaining peak anopheline densities in early spring (1948) as shown in Fig. 13.

The two weeks in mid-May and each week in June and July, 1948 showed weekly mean humidities lower than usual, dropping sharply in May to critical levels. In June, mean RH was 40.8 per cent, 10.4 per cent below the normal for that month. This may explain the corresponding sharp June drop in anopheline densities shown in the curve. However, if such collections could have been repeated over several years, we feel that a smoother anopheline density curve would have resulted. At any rate, the general pattern shown here is probably characteristic and certainly is well correlated with spring and fall peaks in malaria morbidity which followed peak anopheline populations.

In summary, we can reiterate that the anopheline population is at its lowest ebb during the midsummer months of July and August, when temperatures are highest and RH are lowest. The vector population increases rather suddenly in October as a result of optimum mosquito-life-cycle temperatures (90° F) reached a few weeks earlier (September), and remains at a fall peak during October and early November. (As additional supporting evidence, our largest single light-trap collections during the period from October, 1948 thru July, 1950 occurred on October 11, 1948 and November 8, 1949). This peak vector population results in a great increase in malaria cases in November and early December. With advent of cooler weather, the life cycle is extended and the population is reduced to its lowest winter level in late January and early February. This is coincident with lowest winter temperatures. It is of special interest to note that the winter-minimal-vector-population densities are still higher than the summer-minimal densities. This is in direct response to the more critical summer conditions of temperature extremes combined with low RH. During this critical summer period, individual vector longevity is also at a minimum.

As spring temperatures increase and humidity remains favorable, the anopheline population increases until a maximum is reached in mid-April and early May. This represents the spring peak in anopheline population and is reflected in the spring malaria-morbidity peak which follows about a month later. This morbidity lag, both in spring and fall, is readily explained by the time required for extrinsic and intrinsic incubation periods in the vector mosquito and human host.

PART IV. SEASONAL VARIATION IN MALARIA MORBIDITY

The seasonal periodicity of malaria in the oases of eastern Saudi Arabia is one of the most interesting phases of the epidemiology of the disease in the area. The relationship between vector density and malaria incidence is usually so close that it has come to be axiomatic in malariology. Usually seasonal fluctuations in malaria morbidity are attributed to seasonal variations affecting the vector population, but effects of temperature on parasite development in the mosquito host and seasonal changes in behavior of the human host with different temperature-humidity conditions are also important factors in the local epidemiology of oasis malaria.

Seasonal rises in incidence are characteristic each spring and fall with May representing the culmination of the spring malaria season and November the peak for the fall season. Outside of these two transitional seasons, the excessively hot summers and the cool winters are relatively malaria-free. Of special epidemiological interest is the fact that our hot dry *summer* months usually show the lowest monthly morbidity rates of the year (Figs. 16–19).

This uneven seasonal distribution of cases is shown in Figure 14 where mean monthly morbidity rates (1941–1957) are plotted with mean proportionate mortality rates. The seasonal pattern in frequency of cases is paralleled by seasonal differences in malaria death rates. Individual monthly malaria morbidity rates over this same period are given in Tables 21 and 22. These data are separated into two tables to illustrate monthly rates both before and after malaria control with residual sprays.

FACTORS DETERMINING SEASONAL DISTRIBUTION

Seasonal variation in incidence is a constant feature of most endemic malaria in the subtropics. Local examples of the great variations that may occur from month to month and year to year are shown in the accompanying tables. In northern India, where a somewhat similar seasonal pattern occurs, the fall rise is usually caused by an increase in both *vivax* and *falciparum* infections. Usually the incidence begins with a preponderance of *vivax*, and *falciparum* increases as the peak of the curve is reached. Following a decline from peak, *malariae* may become more conspicuous (as a result of residual infections) especially during the winter months (Gill, 1938).

Unfortunately, for 1947 (the last year before control measures were instituted) and for most earlier years, we do not have accurate data on species of parasite involved in the development of this local seasonal epidemic rise. The demands on the Aramco hospital laboratories were so great during this peak season that almost 80 per cent of the malaria cases had to be diagnosed clinically. The remainder were identified as *falciparum* (18%) and *vivax* (3%). Hospital facilities were so taxed in the November-December epidemic of that year that arbitrary allocations of hospital beds to fevers of 102° F and above were made. Lesser degrees of fever had to be treated on an out-patient basis with employees remaining in quarters during their illness! As a result of this crisis, some potentially very interesting statistical data on species composition of seasonal waves could not be collected and are not available elsewhere.

Rainfall. In the area of our studies, the seasonal winter rainfall is of little or no importance in the epidemiology of malaria. Conceivably, heavy winter rainfall, especially late in the season, may contribute to more extensive breeding places for anophelines during the spring malaria season. But in most of our irrigated oasis areas excess rainfall is largely carried away by the network of drainage canals involved in the local irrigation system. In any event, breeding places exist in quantity the year round; and any increase in surface-water accumulation is more definitely connected with seasonal changes in need for irrigation water, in relative humidity, and in evaporation rates which in turn affect the water table. Under these unusual circumstances no *local* rainfall is needed to maintain a high level of endemic malaria in the oases under study.

Relative humidity. Humidity plays a far more important role than rainfall. Its most important effect is on the longevity of the anopheline vector. Low RH shortens the life span of the mosquito. When this life span drops below the minimum extrinsic incubation period, transmission obviously stops. Humidity also affects biting habits; mosquitoes are more active and feed more frequently under hot, humid conditions. Hence chances for an infective bite are increased.

We feel there is good reason to believe that the drop in RH to an unfavorable level in early summer abruptly shortens vector longevity and

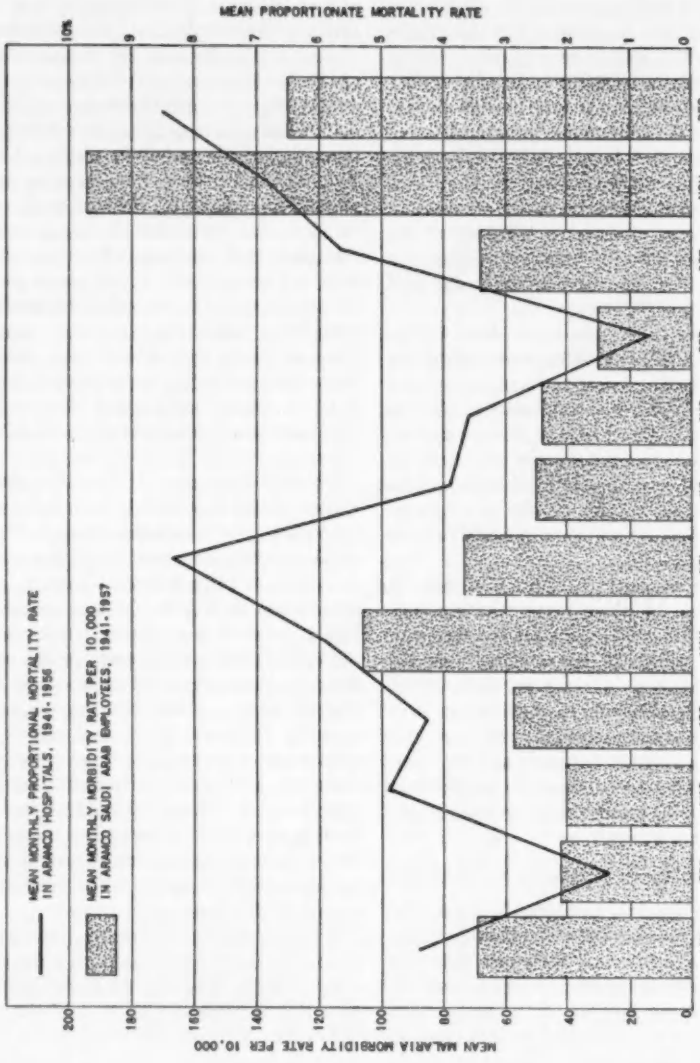

FIG. 14. Seasonal pattern of malaria morbidity and mortality, Qatif oasis

TABLE 21

Pre-control malaria morbidity rates per 10,000 in Saudi Arab employees Arabian American Oil Company, 1941–1948*

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual†
1941	30.2	47.8	66.5	109.1	118.9	79.0	229.2	213.6	198.3	273.0	445.9	394.7	2,206.2
1942	181.4	108.8	84.0	136.6	380.3	71.4	47.1	88.7	23.7	88.7	149.6	314.4	1,674.7
1943	177.7	98.1	21.6	67.7	195.4	159.8	58.8	72.3	52.7	256.5	721.8	434.6	2,317.0
1944	190.0	97.5	69.2	231.3	235.8	154.7	124.2	20.9	4.8	66.2	173.6	100.9	1,469.1
1945	55.7	19.7	66.6	49.4	134.6	114.7	23.7	38.1	10.8	61.9	161.9	265.9	1,003.0
1946	109.0	67.4	55.3	67.9	105.7	126.4	127.3	81.5	23.4	91.0	112.8	134.3	1,102.0
1947	120.9	92.9	126.3	190.2	254.6	244.7	85.8	73.1	25.8	52.2	638.8	277.1	2,182.4
1948	209.0	120.8	118.6	26.7	182.2	147.5	68.9	107.1	48.5	60.0	Control with DDT residual sprays began Oct. 1948		(1,132.0)
Mean.....	134.2	81.6	76.0	109.9	200.9	137.3	95.6	86.9	48.5	118.7	343.5	274.6	1,631.2

* Some non-employees may be included through March 1947.

† These annual totals will differ somewhat from those given in Table 7 and in Figure 20 where mid-year (June) employee populations were used in calculations of overall annual morbidity rates. In this table, monthly employee populations were used in calculation of monthly rates. The annual rates shown here are sums of the monthly rates.

cuts transmission sharply in our oases. A sudden return to favorable humidity permits longevity to increase so that transmission again proceeds unchecked providing temperatures are favorable. This results in a dramatic fall increase in our malaria incidence each year.

Temperature. The effects of temperature are difficult to separate from those of RH. A threshold temperature of 60° F is considered necessary before any *Plasmodium* can complete its development. Locally, mean daily temperatures below these low levels may be reached; but they are seldom maintained for more than a few days. Occasionally, mean monthly temperatures as low as 56° F may be reached in January and February; but 12-year averages show 60° F or above to be more normal even for the coldest months. For all practical purposes then, our lowest winter temperatures may greatly extend the extrinsic incubation period and reduce vector populations; but they probably do not totally prohibit the transmission of *vivax* or *malariae* malaria in these coastal areas. *Falciparum* malaria may be affected for a few of the colder weeks of the year. Malaria morbidity may thus be at a very low level in winter, but some transmission can theoretically continue even during the coldest months of the year.

A critical temperature exists at a higher level where anophelines can survive (if humidity is favorable), but sporozoite development in the vector is not completed. This limiting effect of high temperatures on malaria transmission occurs in the range of 90 to 95° F and varies somewhat for different species and strains of malaria parasites. These high temperatures can "sterilize" an already infected mosquito if exposure continues for only a few hours. Stratman-Thomas (1940) found *vivax* more susceptible to high temperatures than to low since even at 90° F oocysts did not go on to develop sporozoites. Our local mean temperatures reach these critical ranges during the summer. Mean weekly temperatures above 90° F normally occur over a 10-week period in late June, July, August and early September.

Relative humidity also reaches its lowest level during the early part of this summer period. Certainly the combination of high temperatures and low RH has a dramatic effect on suppressing malaria transmission locally. As a result, our mid-summer months are, relatively, our most malaria-free period.

The combined action of high temperature and high humidity on the human host is another local factor of epidemiological importance. During the late summer and early fall, a most uncomfortable

TABLE 22

Post-control malaria morbidity rates per 10,000 in Saudi Arab employees, Arabian American Oil Company, 1948–1957

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual*
1948	No malaria control until October 1948										22.3	20.4	(1,132.0)
1949	9.8	2.5	1.6	6.0	17.7	4.6	4.8	1.0	2.1	8.4	18.5	11.0	88.0
1950	2.0	2.0	1.0	0.0	2.1	3.1	0.0	2.1	2.0	6.7	37.4	31.6	90.0
1951	4.5	3.5	4.4	1.7	16.4	5.1	2.6	2.5	5.0	6.3	46.6	13.8	112.4
1952	0.7	0.7	0.0	0.7	7.7	2.1	1.4	3.4	1.4	2.0	62.4	10.1	92.6
1953	0.7	1.4	1.4	0.7	7.1	7.2	0.0	0.7	4.9	20.5	330.8	51.6	427.0
1954	23.8	14.1	18.5	22.2	36.9	36.4	19.9	27.7	39.7	91.9	311.3	129.7	772.1
1955	43.3	13.6	18.7	31.7	73.9	68.8	37.4	48.0	48.3	53.4	45.4	19.4	501.9
1956	9.8	4.5	5.3	6.0	5.3	8.3	4.5	12.1	12.1	17.3	9.1	3.0	97.3
1957	0.8	3.1	1.5	4.6	1.6	5.5	1.5	6.2	8.6	4.7	3.1	0.8	42.0
1948–57 mean	10.6	5.0	5.8	8.2	18.7	15.7	8.0	11.5	13.8	23.5	88.7	29.1	247.0
1941–57 mean	68.8	41.1	38.9	56.0	104.5	72.9	49.2	47.0	30.1	68.4	193.6	130.2	900.6
1958	3.2	2.4	0.0	0.8	0.0	2.4	1.6	0.8	4.9	5.8	5.8	0.8	28.5

* These annual totals will differ somewhat from those given in Fig. 20 where midyear (June) employee populations were used in calculations of overall annual morbidity rates. In this table, monthly employee populations were used in calculation of monthly rates. The annual totals shown here are sums of the monthly totals.

combination of high temperature and high humidity results in large numbers of people sleeping out of doors or on rooftops in the villages in order to allow a slight breeze to increase their comfort at night. Thus human exposure is increased at precisely the same time that conditions of temperature and humidity become optimal for vector and parasite. This only emphasizes the sudden normal rise in malaria incidence in November.

TEMPERATURE AND HUMIDITY EFFECTS ON FREQUENCY OF INFECTIVE BLOOD MEALS

The first blood meal of an adult female *stephensi* is usually taken during its first night, 8 to 24 hours after emergence from the pupa (Knowles and Basu, 1943). The frequency of subsequent feeds is dependent on rate of digestion, which varies with season; being slower in winter and more rapid in summer. It is most rapid in hot, humid weather. At these times blood meals *may be taken nightly*. This effect of hot, humid weather in increasing the frequency of blood meals is another important ecological factor helping to explain the rapid build-up of our malaria cases in November, immediately following the period of hot, humid weather (September and October) so characteristic of late summer throughout the Persian Gulf area.

June, July and August are hot, dry months (see tables on weather data). Mayne (1930), in India, noted that in these hot, dry months digestion of blood in engorged mosquitoes required 3 to 5 days; but that when RH was increased, the intestinal tract was cleared in 1 to 3 days. This probably means that the number of blood meals in our vector anophelines is necessarily decreased during this hot, *dry* period; thus decreasing the chances of the vector anopheline to obtain an infective blood meal.

INFLUENCE OF TEMPERATURE ON VECTOR INFECTION IN RELATION TO GAMETOCYTE DENSITY

Density and sex ratio of gametocytes vary widely from one patient to the next and at different periods of acute illness. It is interesting to note that temperature during the extrinsic incubation period may influence the "take", particularly when gametocyte densities in the human host are low. Knowles and Basu (1943) found that incidence of infection in *stephensi* artificially infected with *vivax* and *falciparum* varied directly with gametocyte density. In studies with *falciparum*, no mosquito infections occurred with gametocyte densities below 100 per mm³ *when incubated at 70° F.* When incubation temperatures

were raised to 80 to 90°, infection *did* take place at these low densities.

Again this is important in our local epidemiology of malaria. The chances of successful vector infection with low gametocyte densities in the human host are thus increased when incubation temperatures rise to 80 to 90° F as opposed to incubation at 70° F. These higher temperatures prevail in late summer when favorable humidities coincide with other optimal factors to result in our maximal seasonal morbidity in November.

TEMPERATURE AND HUMIDITY EFFECTS ON EXTRINSIC INCUBATION PERIOD

The detailed effects of varying temperatures and humidities on malaria parasite development in various vector species have been the subject of many investigations. Apparently, there are minor differences in these reactions in *strains* (of the same species) as well as in *species* of the parasite. Minor differences are also dependent upon the particular vector in question. Indian strains of *vivax* and *falciparum* apparently continue to develop at higher temperatures (maximum about 90° F) than strains from more temperate regions (Siddons, 1944). Since Arabian strains may be similar to Indian, we have relied largely upon experimental data in the literature describing studies made in India, on Indian strains of the parasite developing in *stephensi* or in a companion species, *culicifacies*.

After reviewing the investigations of Mayne (1930), Strickland, Roy and Chaudhuri (1933, 1936), Knowles and Basu (1943), and Siddons (1944) in India on parasite development and those of Pal (1943), Dakshinamurty and Sharma (1951a, 1951b), and Lal (1953) on vector development, a synoptic temperature-humidity scale for evaluating our malaria epidemiology was developed (Table 23).

In comparing this scale with our average local temperature-humidity conditions (Table 6 and Fig. 15), these facts become important in local epidemiology of malaria. In an average year:

1) Winter mean temperatures do not go below thresholds for parasite or vector; hence transmission can proceed slowly and at a very low level even during the coldest months of the year.
2) When spring and fall optimum extrinsic incubation period (EIP) temperatures of 80 to 82° F are reached, relative humidity is at a favorable 60% or higher in these oases.
3) When late spring and early fall higher-than-optimum EIP temperatures reach 86° F (upper limit of favorable range), the accompanying mean RH are relatively unfavorable (under 60%) for vector longevity needed for completion of EIP.
4) In effect, 86° F becomes a *controlling temperature* in our local malaria epidemiology, above which parasite development is more and more retarded. Transmission is further reduced because accompanying low RH (usually occurring with 86° F and above) reduces vector longevity to a point where parasites cannot complete their development before the vector dies.
5) At 90° F, parasite development almost ceases in spite of any high humidity which may accompany these high temperatures to favor vector survival.

Applying the data summarized in Table 23, we can test the above assumptions by applying them to our standard, seasonal, pattern of malaria morbidity derived from precontrol, mean monthly-morbidity rates (1941–1948), mean weekly temperatures (1945–1956), and mean weekly 0900 humidities (1945–1949). The interrelationships of these data are shown in Fig. 15.

STANDARD SEASONAL PATTERN IN MALARIA MORBIDITY

A standard seasonal pattern of mean, monthly malaria morbidity in relation to mean weekly temperatures and RH (from 0900 readings) has been constructed from data previously outlined. In our hypothetical standard malaria cycle (Fig. 15), temperatures of 70 to 86° F, favorable for parasites, with 60 per cent mean RH, begin in late March. Optimum temperatures for parasite development in the anopheline host (80–82°) are reached about May 1.[2] By the end of May, 86° F, the upper limit of the range, favorable to parasites, has been reached; but by mid-May the mean RH is becoming relatively unfavorable for the vector, dropping to 57 per cent. Although optimum vector-developmental temperatures (90° F) have not yet been reached by mid-May, the decrease in RH beginning at this time tends to make conditions unfavorable for adult *stephensi*

[2] In the fall, this parasite optimum is *preceded* by the vector optimum; hence a much larger vector population is available to take advantage of optimum parasite temperatures. This "advantage" does not occur in the spring.

TABLE 23

Temperature-humidity effects on malaria transmission

TEMP. SCALE	VECTOR TRANSMISSION	MEAN TEMP. - HUMIDITY	PARASITE DEVELOPMENT	VECTOR DEVELOPMENT
50°F	*No transmission.*	50° with 50-100% R.H.	No development.	Above vector THRESHOLD but development retarded.
60°	*High relative humidity not essential for transmission in this temperature range. Transmission occurs readily at 60% R.H. and above - even as low as 45%-50% R.H.*	60°	THRESHOLD.	Improved development but still slow.
		65° with 80% R.H.		Adults survive 33 days.
70°		70°	Lower limit of favorable range, 14-15 days EIP.	
		77° with 60% R.H.		Lower limits of favorable range. Adults survive 28 days.
		77° with 20% R.H.		Adults survive 14 days.
80°	*Higher humidity becomes increasingly important with higher temperatures in this range. 60%-70% R.H. required by vector for EIP survival and transmission.*	80°-82°	OPTIMUM - heaviest sporozoite development, 10-11 days EIP.	
		86° with 60% R.H.	EIP 8-9 days.	Adults survive 18 days.
		86° with 20% R.H.		Adults survive only 6 days (sporozoite development impossible).
		86°	Upper limit of favorable range.	
90°	*Little or no transmission.*	90°	CRITICAL - few or no sporozoites formed in 9 days EIP.	OPTIMUM - life cycle reduced to 7-8 days.
		93°		Upper limit of favorable range.
		94°	Oocysts disintegrate.	
		95° with 80% R.H.		Adults survive 10 days.
	No sporozoites develop.	95° with 20% R.H.		Adults survive only 6 days.
	No transmission occurs.	99°		Larvae develop rapidly, but do not pupate.
100°	*Higher humidity cannot compensate for temperature extremes in this range to allow necessary vector survival.*	104° with 20%-100% R.H.		CRITICAL - adults survive only 19 hours.
		107°		Thermal death point for pupae (1 hour exposure).
110°				
120°		122° with 20% R.H.		Adults survive only 5 minute exposure.
		123°		Thermal death point for eggs (1 hour exposure).

EIP Temperature Limits

EIP Temperature Limits

NOTE: EIP = Extrinsic Incubation Period.

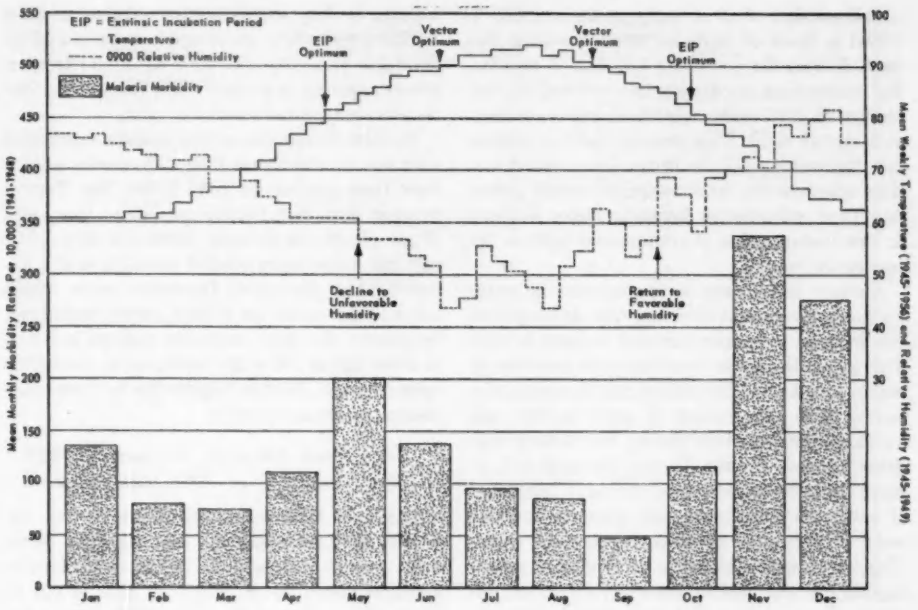

FIG. 15. Standard seasonal pattern of malaria morbidity in relation to temperature and humidity, Qatif oasis

longevity. Presumably, if RH were to remain at 60 per cent (preferably above this figure with the higher temperatures), the vector population might continue to increase throughout the favorable-temperature range for vector development (77°–93° F). But instead, humidities become even more unfavorable and remain so until late August when 55–60 per cent RH is again reached thus ending the "dry" portion of the summer. As a result of this early summer combination of high temperatures and lowered humidity, decreased malaria transmission occurs; and the June morbidity rate normally heralds the beginning of the summer decline.

Through the hot summer (late May, June, July and early August), mean RH remains low and thus keeps the vector population in check or short-lived and ineffective as vectors. Mean temperatures continue to increase until 90° F is reached late in June. Temperatures remain at 90° F or above (weekly means of 92–94° F in July and most of August) until early September. Even though the more favorable humidity beginning in late August might allow some improvement in vector survival during the latter part of this period, the 90° F+ critical temperatures in themselves effectively reduce or halt parasite development. Thus July, August and September are usually our least malarious months (see Figs. 15–19).

Once mean temperatures begin to drop below 90° F in mid-September, favorable transmission conditions begin to reappear. Optimum vector-developmental temperatures (90° F) begin in early September, allowing a long period for maximum population build-up in the vector before the EIP optimum is reached. This is followed by temperatures (86–70° F) favorable for parasites in late September through November. Optimum EIP temperatures (80–82°) occur in mid-October about 6 weeks after the vector optimum is reached. With favorable humidities during this period (above 60%), a large vector population with sufficient longevity is at hand to take advantage of the ideal transmission conditions in October.[3]

[3] This is theoretically the reverse of the spring situation where temperatures optimum for vectors are obviated by low humidities before the population can increase to its "temperature potential."

Still another effect of temperature-humidity is added in favor of increased transmission at this time. During the preceding hot, humid months, the human-host population has reverted to roof tops or to outdoor courtyards for more comfortable rest at night. This seasonal habit continues into the beginning of the transmission season and thus improves the man-mosquito contact potential. Thus, still another favorable factor is added to this juxtaposition of transmission optima occurring in October.

Another coincidence is the increase in water surface for mosquito breeding that accompanies the decrease in temperature and increase in RH. This is due largely to local irrigation practice, in which the land under cultivation is necessarily restricted to the amount of water needed and available for irrigation during the hottest and driest summer months. During the early fall, irrigation needs are less; but the same quantities of water flow from springs and uncapped artesian wells regardless of decrease in seasonal needs. This excess irrigation water accumulates, waterlogging the soil, raising the water table, and increasing the surface water to form additional breeding places for *stephensi* at this time.

This sudden overlap of favorable conditions in October: optimum EIP temperatures, maximum vector population, extended vector longevity for parasite incubation, more frequent feedings by vector, improved mosquito infection at lower gametocyte densities, and increased exposure of the human host, is "triggered" by the sudden return of favorable humidity. The result is a spectacular increase in fall malaria as shown (after appropriate incubation lags) by our November peak-morbidity rates.

By mid-November, mean temperatures have dropped below the favored range for *stephensi* (93°–77° F) and, by the end of the month, below the favored range for parasite development (86°–70°). Thus, in spite of favorable humidity, cooler weather acts as an effective check on transmission. December and January morbidity rates decline, reaching winter lows in February and March. With the increase in temperature in early spring, the seasonal cycle begins again.

With minor seasonal shifts, this same pattern is seen in all of our monthly morbidity data (Tables 21 and 22). A characteristic seasonal curve (Fig. 15) with a gradual rise in spring to a May peak; a rather sharp drop with hot, dry weather in July to minimal seasonal morbidities during the summer; an abrupt increase set off by favorable humidity and more moderate temperatures resulting in a spectacular fall peak in November; is repeated year after year.

In order to compare actual malaria experience with the standard year (Fig. 15), similar graphs have been plotted for 1945 (when Ras Tanura weather data first became available) thru 1948 (Figs. 16–19). In October, 1948, the first DDT residual sprays were applied resulting in the unusually low November-December rates which followed the initial use of this control technique. In general, the same morbidity pattern is shown in these figures although variations in morbidity rates do occur. Factors responsible for these variations are discussed below.

Controlling Effects of Critical EIP Temperatures of 90°F and Above

The year 1945 was characterized by an unusually long, hot summer (see Fig. 16). June, July, August and the first 2 weeks of September averaged above 90° F. The only year in our 12 years of weather data (1945–1956) surpassing 1945 was 1951 in which 90° F+ temperatures persisted a week longer. Mean monthly RH during this hot summer of 1945 was above average, close to 60 per cent or above (June, mean +7.2%; July, mean +8.8%; August, mean +7.8%; September, mean +6.3%; and October, mean +7.0%).

Since the June-to-early-September temperatures were above the critical EIP temperature of 90° F, transmission was almost nil during this period. The higher-than-average humidities tending to favor vector survival could not compensate for these extremes in temperature critical for the parasite. As a result, the July-September 1945 morbidity rates were the lowest recorded for those precontrol years where temperature data are available for analysis (1945–1948). These monthly rates are: July, 23.7/10,000 (mean −71.9); August, 38.1/10,000 (mean −48.8); September, 10.8/10,000 (mean −37.7) (see Table 21).

Late October, 1945, continued warmer than usual, with mean temperatures in the 3rd week of 84.4° F (mean +3.1°) and in the 4th week of 81.4° (mean +2.3°). Thus, the normal optimum EIP temperatures of 80° to 82°, when they did arrive, were delayed from the normally expected

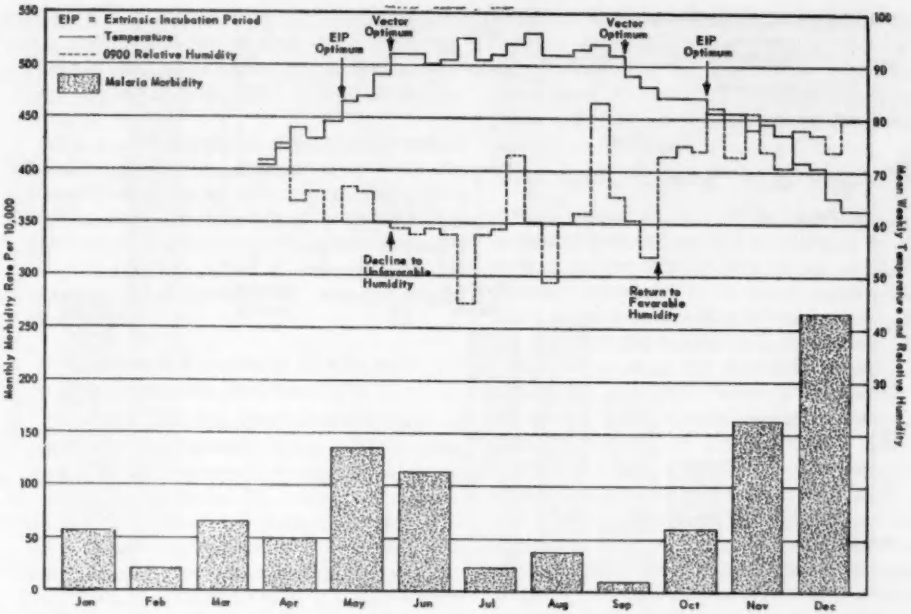

FIG. 16. Seasonal malaria incidence in relation to temperature and humidity, Qatif oasis, 1945

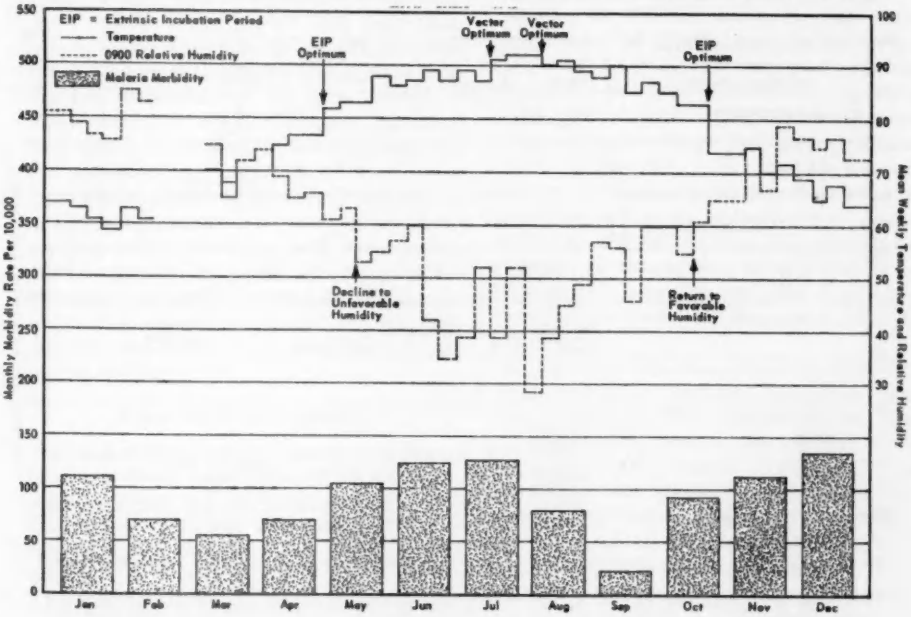

FIG. 17. Seasonal malaria incidence in relation to temperature and humidity, Qatif oasis, 1946

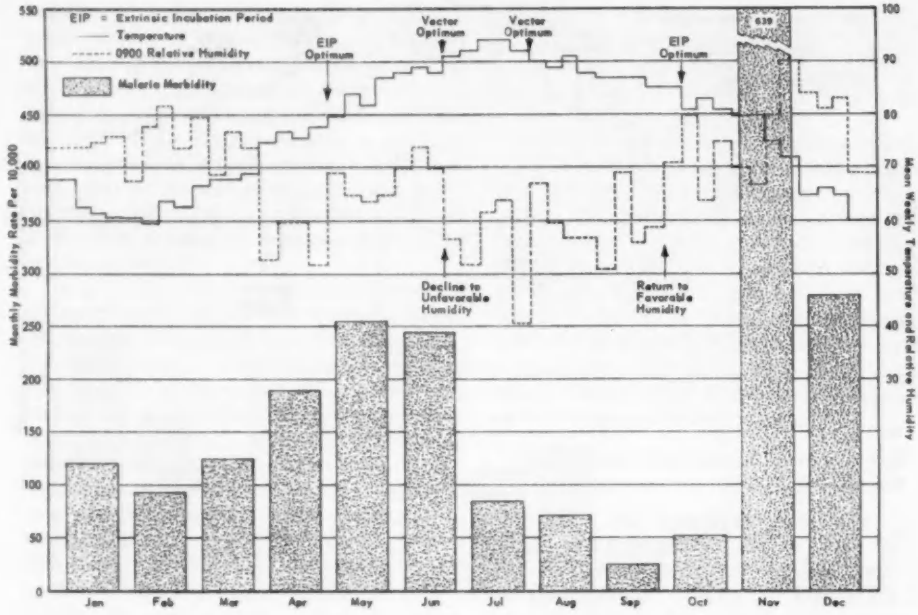

FIG. 18. Seasonal malaria incidence in relation to temperature and humidity, Qatif oasis, 1947

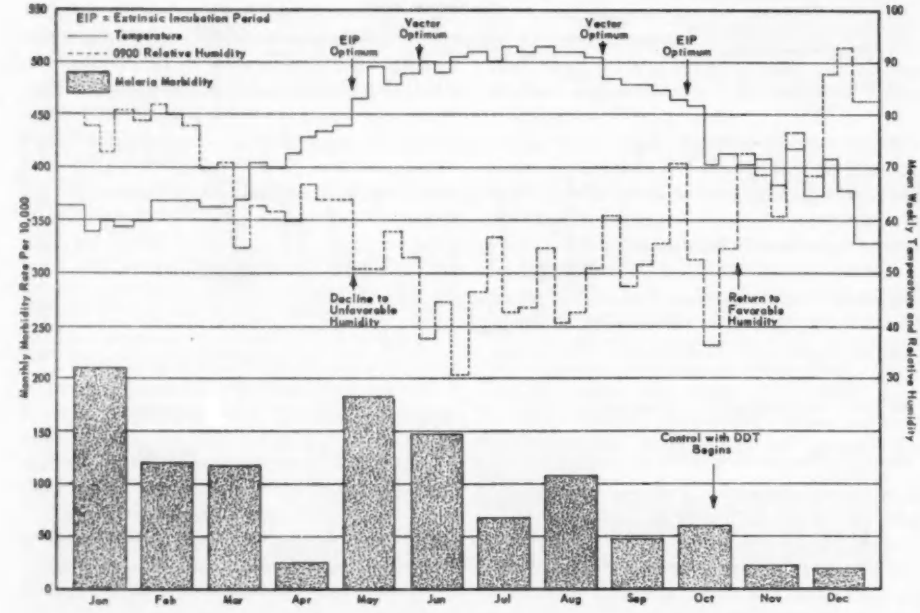

FIG. 19. Seasonal malaria incidence in relation to temperature and humidity, Qatif oasis, 1948

period in mid-October to the last week of October and early November in 1945. As a result, the 1945 fall peak in morbidity was delayed accordingly, occurring in December instead of November (Fig. 16).

This is our best example of the primary control exerted by high temperatures directly on the parasite. The higher-than-average humidities may have mitigated the effects of extreme temperatures on the vector, but these more favorable humidities had no effect in improving malaria transmission at these critical parasite temperature levels.

Retarding Effects of Lower-than-average Temperatures

The April, 1948, morbidity of 26.7/10,000 is an example of a subaverage (mean −83.2) spring morbidity rate apparently due to effects of subaverage temperatures. On analysis of weather records, both March and early April, 1948, were found to be cooler than usual. This 6-week period showed weekly temperature differences considerably lower than average: 62.9° F (mean −2.8°); 63.0° (mean −4.0°); 64.1° (mean −3.2°); 71.3° (mean +1.3°); 69.6° (mean −2.4°); and 73.4° (mean −2.0°). Not only were these cooler-than-normal temperatures keeping the EIP at almost threshold levels as far as development of the parasite was concerned, but the usual increase in vector population was also retarded. This meant that normal vector attrition was occurring without normal replacement. This effect on vector population is possibly reflected in the unusual dip in anopheline population curve shown for March and early April, 1948, in Figure 13. The end result was an unusually low April morbidity (Fig. 19). Once April temperatures began to increase and approach normal means, transmission improved and May morbidity rates reflected these more normal conditions.

Major Seasonal Epidemics

Even a cursory examination of available precontrol morbidity data (Table 21) will show some years and some seasons to be more malarious than others. November epidemics in 1943 and 1947 are good examples of these major seasonal outbreaks. A review of accompanying weather data preceding these unusual peaks can usually assist in giving an explanation in terms of variation from the standard climatic pattern just portrayed. One example of such a major seasonal epidemic can be found in November, 1947 (Fig. 18). Weather data are available to help reconstruct some of the factors probably responsible. From such a reconstruction, criteria for prediction can be developed.

Predicting Unusual Fall Morbidity

Since unusual fall and spring epidemics of uncontrolled malaria may put an excessive burden on local medical-care facilities, it may be of considerable importance to be able to predict such heavy seasonal outbreaks in advance so that adequate preparation can be made for patient care.

In order to study the possibility of such prediction, the fall, 1947, outbreak was chosen to represent a major seasonal epidemic, while fall, 1946, represented an unusually light season. These years were selected from the precontrol period, 1941 to 1948, on the basis of their maximal and minimal November morbidity rates.[4] Differences in fall and spring morbidity rates and related weather conditions from expected means are given in Table 24. More graphic presentations of the malaria situation in the years 1946 and 1947 are given in Figures 17 and 18.

During the 1947 fall season, favorable vector temperatures (93°–77° F) began the last week in July, about 2 weeks earlier than usual and lasted through the 3rd week in November (15 weeks). These more favorable temperatures occurring earlier and lasting longer than usual could have allowed an unusually long period for unusually high vector densities to develop. But during this period the high mean temperatures of August-September (90°–85° F) were still relatively unfavorable for the parasite. Temperatures during these months were only beginning their decline from the critical level inhibiting parasite development.

In October, 1947, these relatively unfavorable situations changed suddenly, particularly in regard to humidity. Mean temperatures gradually approximated the parasite optimum (80°–82° F). Relative humidity, however, increased from below 60 per cent during 3 September weeks to above 70 per cent during 3 October weeks; a highly unusual but highly favorable humidity for the vector in this temperature range.

Thus, in retrospect, an unusually long and

[4] 1943 was obviously an epidemic year as well, but weather data are not available for analysis.

TABLE 24

Temperature-humidity analysis of Fall and Spring malaria epidemics, Qatif Oasis

Month	Standard fall malaria season			Fall epidemic —1947			Fall sub-average season—1946		
	Rate/ 10,000[1]	Mean temp.[2]	Mean R.H.[3]	Mean rate/10,000	Mean temp.	Mean R.H.	Mean rate/10,000	Mean temp.	Mean R.H.
August	86.9	92.5°	50.1%	−13.8	−2.9°	+9.8%	−5.4	−2.3°	−8.7%
September	48.5	88.1°	58.4%	−22.7	−1.9°	+0.4%	−25.1	−0.4°	−2.9%
October	118.7	81.7°	64.9%	−66.5	+0.3°	+7.8%	−27.7	−1.4°	−4.1%
November	343.5	73.7°	73.6%	+295.3	+2.8°	+4.0%	−230.7	−1.2°	−1.7%
December	274.6	64.8°	78.4%	+2.5	−1.0°	−0.2%	−140.3	+1.4°	−3.4%
	Standard spring malaria season			Spring epidemic—1947			Spring sub-average season—1946		
March	76.0	67.8°	69.5%	+50.3	+0.3°	+5.5%	−20.7	+4.2°	+3.1%
April	109.9	76.0°	62.7%	+80.3	+0.3°	−6.8%	−42.0	−1.3°	+5.5%
May	200.9	84.3°	58.2%	+53.7	−0.6°	+7.6%	−95.2		−0.4%
June	137.3	89.2°	51.2%	+107.4	−0.3°	+15.9%	−10.9	−1.8°	−4.1%
July	95.6	92.5°	51.4%	−9.8	+0.5°	+2.1%	+31.7	−2.4°	−5.5%

[1] Mean monthly morbidity rates/10,000 Saudi Arab employees (1941–1948).
[2] Mean monthly temperatures (°F), Ras Tanura, (1945–1956).
[3] Mean monthly relative humidity (0900 readings), Ras Tanura (1945–1949).

favorable vector developmental period may have resulted in an unusually high vector density. Its effective longevity and hence transmission potential, however, was held in check until October by unfavorable humidity. This check was suddenly released by a return to not only favorable humidity but to unusually favorable humidity for October, allowing the "higher-than-usual" vector population to be "more-effective-than-usual" transmitters. Hence, the unusual November outbreak in 1947 (see Fig. 18).

Conversely, the fall, 1946, season differed markedly in these same factors (see Fig. 17). Favorable vector temperatures (93°–77° F) were not exceeded during the entire summer, but they were interrupted and the favorable-development period checked by a sudden, sharp temperature drop in the third week in October. By contrast, comparable favorable humidities of above 60 per cent were not reached until this same third week in October in 1946, whereas in 1947 early October humidities rose above 70 per cent to make unusually favorable transmission conditions. These unusually unfavorable humidities for October held the anopheline population in even longer and closer check as far as longevity (and hence transmission potential) was concerned. This check was not released until cooler November temperatures had already replaced low humidity as a deterrent to optimum transmission. Hence, the November-December morbidity rates were much lower than would otherwise have been expected (compare Figs. 15 and 17).

Pertinent data from our standard fall malaria season, the 1947 epidemic, and the 1946 sub-average year just described are given in the accompanying tables and figures. From an analysis of these data we have offered a hypothetical explanation of "good" and "bad" malaria seasons in relation to an "average" one. Apparently October is the key month for predicting whether the following November peak will be higher, lower, or about equal to the average.

As pointed out previously, the seasonal temperature cycle is remarkably constant and seems to vary only slightly from year to year. In the "good" and "bad" years just described, mean monthly October temperatures varied only slightly from the average 81.7° F (mean +0.3° in 1947; mean −1.4° in 1946); but the weekly means in October, 1946, showed considerable variation (see Fig. 17) from the October standard.

In RH, the reverse was true. The two comparable October 0900 mean monthly RH differed considerably (mean +7.8% in 1947; mean −4.1% in 1946) from that of the average 64.9 per cent RH usually experienced. This difference was also reflected in the weekly means. As we have seen from our previous discussions on the effects of RH on vector longevity, this factor be-

comes most important at higher temperatures. Unusually low humidity during this warmer part of the transmission period reduces longevity, frequency of feeding, host exposure, and hence potential transmission. Unusually high humidity in October increases transmission by extending vector longevity and increasing frequency of blood meals. The accompanying discomfort, caused by high humidity and heat also results in greater chances for effective vector-host night contact. Thus, unusual shifts from the normal October humidity seem to have a most significant effect on November morbidity rates.

From the above, we can predict that November will be more malarious than usual if October mean RH (0900 readings) are above the normal 65 per cent and approach 70 per cent or higher. November will be less malarious than usual if these mean RH are less than 65 per cent and decline to 60 per cent or lower. This is based on the assumption that there are neither great variation from the mean monthly October temperature of 82° F nor extremes in the weekly means, to affect transmission. If October temperatures continue to be abnormally high, the fall peak may be delayed until December, rather than occurring in November.

Predicting Unusual Spring Morbidity

Unusual variations from the spring pattern do not occur to the same degree as we have just seen in the fall (see Table 24). Fall rates varied from a mean +295.3 (November, 1947) to a mean −230.7 (November, 1946). By contrast, the spring rate variations available for study were much less striking, ranging from a mean +53.7 (May, 1947) to a mean −95.2 (May, 1946). The entire explanation for these differences perhaps cannot be made on the basis of temperature and humidity. A spring relapse wave as described by Gill (1938) may also cloud the picture, but unfortunately our data do not distinguish new infections from relapses.

One very important climatic difference between the spring and fall patterns is the fact that optimal EIP temperatures (80°–82° F) are approached from lower temperatures in the spring and from higher temperatures in the fall. We know from previous investigations that changes in RH exert little influence on vector transmission on the lower side of the optimum 80°–82° F, but they are most significant on the upper side. Thus, the normally-more-varying RH do not have the same opportunity to affect the developing spring morbidity peak as we have seen in the developing fall peak.

Another important spring factor is the occurrence of the vector optimum (90° F) *after* the EIP optimum (80°–82° F) has already been reached. Hence, there is not the opportunity of a large anopheline population to build up in advance and to make the most of the sudden favorable humidities that normally occurs in the fall.

Since high temperatures are usually unvarying enough to inhibit transmission in July, no matter how high the humidity, the spring pattern is usually more rigid. As a result, spring malaria is usually less variable, more stable, and very great variations from the expected do not occur. Extensions of favorable, moderate temperatures may extend the peak period into the summer; but extreme variations in the size of the peak are relatively uncommon; certainly not seen as readily as corresponding fall variations in peak size.

With these reservations, we can attempt an analysis of the more limited variations of the 1947 ("high") and 1946 ("low") spring malaria seasons in comparison with the standard seasonal pattern (see Figs. 15, 17, and 18).

In 1947, spring temperatures were average. Favorable transmission temperatures (77°–86° F) began in mid-April as usual with optimum EIP temperatures (80°–82° F) occurring the first week in May. Critical EIP temperatures of 90° F occurred as expected in the last week in June, as did the resulting normal seasonal morbidity drop in July.

Humidities in 1947 remained at above average levels in May and June but broke sharply the last week in June. Unusually favorable May humidities kept the June rate at May levels instead of permitting the normal reduction which characterizes expected June morbidity. The sudden drop in humidity in late June, occurring with expected critical temperatures of 90° F, resulted in an unusually sudden drop in malaria morbidity experienced in July, 1947. Even the unusually favorable June humidities in the first 3-weeks could not compensate for the near-90° F temperatures being approached at this time. Thus, the unusual spring outbreak in May-June 1947 is attributed to an extension of favorable humidity beyond the expected mid-May decline to unfavorable humidity.

In early spring, 1946, temperatures were comparable to those of 1947 and to the normal pattern both in degree and timing. The major difference between the two years was the occurrence of more moderate temperatures which continued from June through the first half of July. Critical EIP temperatures of 90° F were not reached in 1946 until 3 weeks later than expected, and this allowed the normal May-June morbidity peak to be extended into July (see Fig. 17).

Weekly humidities dropped below 60 per cent by mid-May, 1946, but rose again to 60 per cent in mid-June when they again suddenly dropped below 50 per cent. This "spotty" improvement in June humidity helped maintain vector survival in the face of the higher temperatures which would otherwise have reduced it. But even these higher temperatures were unusually delayed in reaching the critical 90° F. The end result was a leveling of the May-June-July rates instead of the sharp drop in July normally expected. This is explained by a combination of milder temperatures and more favorable humidity than would normally have been expected at this season.

On the basis of the above examples, we can predict as follows: 1) If May RH is above average, a higher June rate than normal can be expected. Supposedly, the converse is true especially when accompanied by average or higher-than-average temperatures, but we have no unusually low May humidities or June morbidity rates available for testing this hypothesis.

2) The normal June break in temperature (90° F) is reflected in the normal July decline in morbidity. If June temperatures remain moderate (below normal for the month) and humidity remains favorable, July morbidity may remain at June levels instead of declining. However, above normal June humidities cannot compensate for critical 90° F temperatures to allow malaria transmission.

Our general review of seasonal malaria cycles with data at hand compares very favorably with the conclusions of Gill (1921) who studied malaria epidemics in the Punjab. On epidemiological grounds, he felt that a mean monthly relative humidity (0800 readings) of 63 per cent or more was required providing temperature was favorable. Temperatures of 61° to 93° F were favorable if humidity conditions were met. At mean temperatures of 60° F and below, or 100° F and above, he believed no transmission to occur. In general, his hypothesis fits our own situation, except that our data indicate some transmission (although much reduced) at mean monthly RH (0900 readings) in the range 50 to 60 per cent RH when temperatures are moderate.

PART V. MALARIA CONTROL WITH RESIDUAL SPRAYS

With much of the previous epidemiological information as a guide, recommendations were made to utilize DDT residual sprays as a primary control measure in the two oases; and a joint program on malaria control utilizing this technique alone was developed between the Saudi Arab Government and Aramco. The first oasis-wide application in the Qatif coastal area in this joint program was made in the fall of 1948 utilizing 5% DDT in kerosene. In the following year (1949) al-Hasa was included in the program for the first time. DDT suspensions of wettable powder were used in 1949 and in successive years through 1954. In 1955, 1956 and 1957, dieldrin suspensions replaced DDT as the residual insecticide of choice. In 1956 and 1957 the field spray operations were carried on by the Ministry of Health while Aramco continued its research investigations on malaria.

Insecticide residues were applied to all shelters in villages included in these programs. For the most part, shelters consisted of dwellings, especially sleeping rooms and privies, as well as stables (Figs. 5 and 6). Types of surfaces to be treated varied from palm thatch and palm-leaf matting to adobe or mud brick and native plaster ("juss"). All of these materials present porous surfaces, and applications of water suspensions of the insecticide were generally made to the point of run-off. Estimated residuals of 200–250 mg/sq ft of DDT and 50 to 70 mg/sq ft of dieldrin were attained. All levels of interior surfaces were treated in accordance with previously-described seasonal changes in resting levels of the vector.

Spray applications were made by local Saudi Arab laborers who were given a brief course of instruction and practice in residual-spray techniques before each spray season. Hand-operated, wheelbarrow-type sprayers with constant pres-

sure tanks were found most useful for work in local villages.

Wherever possible, efforts were made to complete residue applications by the end of September each year, so that insecticide deposits would be at maximum strength and effectiveness during the optimum-transmission season. Once applied, it was hoped that residue effectiveness would extend not only through the winter months but also throughout the following spring malaria season. The hot, dry summer would then inhibit malaria transmission until the residues were reapplied in the next annual fall spray program.

This careful timing is apparently less essential with dieldrin than with DDT because of dieldrin's longer lasting effect (more than 12 months). However, it is still advisable to plan completion of the annual spray program just before October, so that any new dwellings constructed during the year, or any shelters missed in the previous program, can be treated *before* the maximum-transmission season in October.

Unfortunately, it was not always possible during our study to repeat the residual spray each fall as we had recommended. For example, in 1950 neither oasis was treated; and in 1952, the Qatif oasis was included in the program but not al-Hasa. In 1954, the al-Hasa part of the program was delayed until early spring, 1955. A chronological summary of these variations in residual-spray programs is given below:

1947, no previous malaria-control measures of any kind in the Eastern Province.

1948, first fall DDT residual-spray program in the Qatif oasis (except Tarut Island); no similar program for al-Hasa.

1949, first fall DDT residual spray program in al-Hasa; entire Qatif oasis (with Tarut Island) also included in program.

1950, DDT residual spray program dropped in both oases, except for continuing program on an experimental basis in the villages of al-Ajam and Safwa (Qatif oasis).

1951, fall DDT residual spray program resumed in both oases.

1952, fall residual spray program continued in Qatif oasis; dropped in al-Hasa.

1953, fall DDT programs resumed in both oases.

1954, fall DDT program in Qatif oasis only; al-Hasa program postponed until spring 1955.

1955, spring DDT residual spray program in al-Hasa except for experimental use of dieldrin in al-Qarah, al-Battaliyah and al-'Umran.
first fall dieldrin residual spray program in Qatif oasis.

1956, fall dieldrin residual spray program in both oases carried out solely by Ministry of Health.

1957, fall dieldrin residual spray program continued by Ministry of Health in both oases in 1957 and 1958.

The variations in control programs indicated above have provided a number of different situations for evaluation of different control measures. The effects of annual, scheduled, residual spray applications, of biennial applications, delays, lapses of 1 year, and the value of DDT vs. dieldrin can thus all be compared.

REACTIONS OF *ANOPHELES STEPHENSI* TO DDT AND DIELDRIN RESIDUES

Hadaway and Barlow (1953) have studied the laboratory reactions of *A. stephensi* to insecticide residues and report that *stephensi* females are activated by contact with DDT deposits (100 mg/sq ft) and fly away from treated surfaces after a few (2 to 4) minutes of contact. This action occurred whether the DDT particles were small or large and whether they were readily available to the insect or adhered firmly to the treated surface. A single contact was lethal only when the spray deposit consisted of small, readily available particles (0–10μ, average 6μ); otherwise the mosquito was stimulated to fly from the surface before acquiring a lethal dose. Mosquitoes would fly on and off treated wallboards, but rested on the untreated surfaces. In some tests, only a 70 per cent kill occurred after a 4-minute exposure before first flight. Similar results occurred with DDT suspensions of 150 mg/sq ft on mud blocks, the latter being more comparable to our adobe construction in al-Hasa.

This irritant action and stimulus to fly from treated surfaces may also force *stephensi* out of more favorable microclimates and into situations much less favorable for survival. In this way, some measure of additional indirect control may compensate for the reduced effectiveness due to irritation and flight from DDT deposits. The importance of this factor as an accessory control will presumably vary with seasonal differences in temperature and humidity in our area.

In comparing *stephensi* reactions to dieldrin deposits, these investigators found no such irritant effect as has been reported for DDT. When *stephensi* adults were exposed to 100 mg of dieldrin/sq ft, no stimulation to flight occurred within a 30-minute exposure period. This exposure resulted in 100 per cent kill within 24 hours. It should be remembered that dieldrin is slower acting than DDT and that mosquitoes may be found resting on dieldrin-treated surfaces several months after application. This does not mean that dieldrin has necessarily lost its effectiveness, since careful observation may show high mortality 24 hours after such exposure. Where adequate dosage is used, dieldrin is long-lasting in its effectiveness. Davidson (1955b) has shown 50 mg dieldrin/sq ft to give 80 per cent kills with *gambiae* for the first year. Even after 2 years, mortality was just below 50 per cent.

Hadaway and Barlow (1957), in experiments with *stephensi*, *Aedes aegypti*, and *Musca domestica*, have shown that DDT *decreases* in toxicity as posttreatment temperatures increase from 68° F to 86° F. Thus local DDT deposits are at minimal efficiency during our optimal transmission temperatures. Dieldrin, on the other hand, shown an *increase* in toxicity with an increase in temperature in this range and hence is at maximum efficiency when it is needed most in our oases.

KILLS NECESSARY FOR EFFECTIVE MALARIA CONTROL

It should be emphasized that malaria can be "controlled" by residual insecticides that fall far short of eliminating the mosquito vector entirely (Macdonald, 1956). Macdonald and Davidson (1953) have constructed an interesting table in which they suggest kills necessary for control under varying conditions. Their suggested necessary kills vary according to the frequency with which a vector species enters a treated shelter: (1) every day ("complete endophilism"), (2) 3 days out of 4 ("moderate endophilism"), and (3) 1 day out of 2 ("medium endophilism"). Original mosquito density is also taken into consideration as well as degree of anthropophilism. They emphasize that species which enter shelters less frequently than indicated above will be more difficult to control with residual insecticides. Thus, with entry not less often than 1 day in 2, half the vector population will come into contact with the residue every 24 hours. Even a low percentage kill on each entry will thus affect the life expectation of the whole population. If, however, entry is infrequent, even a high kill on each occasion will have little effect on the average expectation of life of the vector population as a whole. Under most natural circumstances, malaria "control" could occur by attaining a mosquito mortality rate of about 65 per cent among those entering treated shelters, and in some common situations by a 45 per cent mortality.

From our observations, we feel that *stephensi* is certainly strongly endophilic; both from its resting habits and in its searches for blood meals. Hence, it probably enters treated shelters with maximum frequency. Thus, even with a relatively poor percentage of kill (30–50% continuous mortality), DDT residues could still prove effective in control if resistance did not develop. This, we feel, is borne out by our reduction in malaria-morbidity rates and in lowered parasite rates in treated villages during those earlier years when DDT was the sole insecticide used. Dieldrin, although slower acting, is more toxic and more effective than DDT. It is longer lasting and does not excite resting mosquitoes to flight. Even without the danger of developing DDT resistance, it is the currently preferred insecticide where residual sprays are used for malaria control in our oases.

EVALUATING SUCCESS OF LOCAL MALARIA CONTROL MEASURES

In our study, it has been impossible to distinguish first infections and subsequent relapses in any of the morbidity or survey data presented. In attempting to interpret morbidity and survey data as yardsticks for measuring success of control efforts, differences in time interval between possible new infections and last relapse with the different types of malaria must be considered. This time interval varies with species and with different strains of the parasite in different geographic areas.

Infections with *P. malariae* may well last a lifetime, but *vivax* infections generally do not last beyond 2 years although there may be strain variations in different areas that will modify this generalization. Although the present study can offer no specific data on normal length of *vivax* infections in the Persian Gulf area, it is generally believed that we are not dealing with a strain having an unusually long relapse interval. For practical purposes, *vivax* infections here are regarded as being limited to 2 to 3 years. Our local

morbidity and survey data seem to support this generalization.

The presence of positive findings of *falciparum* is generally considered an indication of recent transmission since infections with this species are usually short lived (9–12 months). Therefore, we have regarded *falciparum* infections seen in our fall village surveys as evidence of malaria transmission during that current calendar year. Our fall morbidity due to *falciparum* infections can also be largely attributed to infections obtained during the calendar year in question.

The *infant parasite index* is a valuable adjunct to the above in any such evaluation since it measures more exactly transmission occurring during the year in question. Unfortunately, it was often difficult to persuade Saudi Arab mothers to bring their infants for blood and spleen examination. In cases where we were successful, the numbers were usually small. Hence, a combination of methods had to be used in evaluation of our control programs and in considering possibilities of future malaria eradication.

RESULTS OF RESIDUAL-SPRAY CAMPAIGNS

The spectacular success of DDT in decreasing malaria morbidity, mortality, spleen and parasite rates was gratifying in the years 1949 through 1953. During this period, our favorable experience paralleled that of many others who had been using DDT for malaria control in other parts of the world. Graphic evidence of the success of these DDT residual-spray campaigns is shown in Figure 20. Here the annual precontrol morbidity rates of 1941 through 48 are contrasted with the successful use of DDT over the period 1949 through 1953. Comparable monthly morbidity rates during these same periods are shown in Tables 21 and 22. This success was also reflected in reduced malaria mortality as shown in Figure 21. A similar reduction was shown, whether malaria deaths were compared with total deaths or only with deaths from other communicable diseases.

The effectiveness of DDT in reducing parasite rates in the villages (1949–1953) is summarized in Figure 22. Here the effectiveness of annual applications is contrasted with biennial applications of DDT residues. The sharp drop to low parasite rates and continued low level of parasitemia with annual DDT applications is shown by data from the experimental towns of Safwa and al-Ajam in the Qatif oasis. The return to high parasite rates each time the annual application was neglected is shown by survey data obtained in the three villages in the al-Hasa oasis. The need for at least annual residue applications is obvious from this chart even though some residual effect may remain for longer than 12 months in earlier years. A more detailed analysis of control programs and results is given by years in the following chronology.

1947. In October, the single village of al-Khobar was treated with 5 per cent DDT in kerosene primarily as a fly-control measure. This gave us an opportunity to test residual-spray equipment and methods on a village-wide basis.

The spectacular seasonal epidemic of malaria in November, 1947, emphasized the seriousness of the local malaria problem. Aramco Saudi Arab employee morbidity rates rose to 639/10,000 in that month. All hospital facilities were so severely strained that only the most seriously ill patients could be hospitalized; others were treated as outpatients. No malaria control had ever been attempted in the area previously.

Initial malaria surveys were made in the fall in Qatif oasis villages to establish bases for evaluation of future control measures (see Tables 11 through 16). An average parasite rate of 85 per cent and spleen rate of 94 per cent in the 2 to 14 year age group was established for uncontrolled villages in the Qatif oasis (see Table 12). Infant parasite rates were 100 per cent; indicating maximum opportunity for infection.

1948. The village of al-Ajam was selected for special study of DDT residual-spray techniques as a result of the 1947 survey. The entire village was treated with 5 per cent DDT in kerosene in March and again in August, just previous to the spring and fall transmission seasons. November parasite rates in the 2 to 14 year age group in this village dropped from 77.4 per cent (1947) to 46.2 in 1948. The greater part of this reduction was due to a marked decline in *falciparum* cases. In 1947, *falciparum* accounted for 33.8 per cent of the positives; in 1948 for only 12.5 per cent. By contrast, *vivax* accounted for 52.3 per cent of the positives in 1947 and 79.2 per cent in 1948. This was to be expected since many of the *vivax* cases probably represented precontrol infections.

Earlier in the year, Aramco had proposed a joint program of malaria control with the Saudi Arab Government utilizing the DDT residual-spray technique. This proposal was accepted, and the first oasis-wide residual-spray program in the Kingdom (Qatif) began in October and was com-

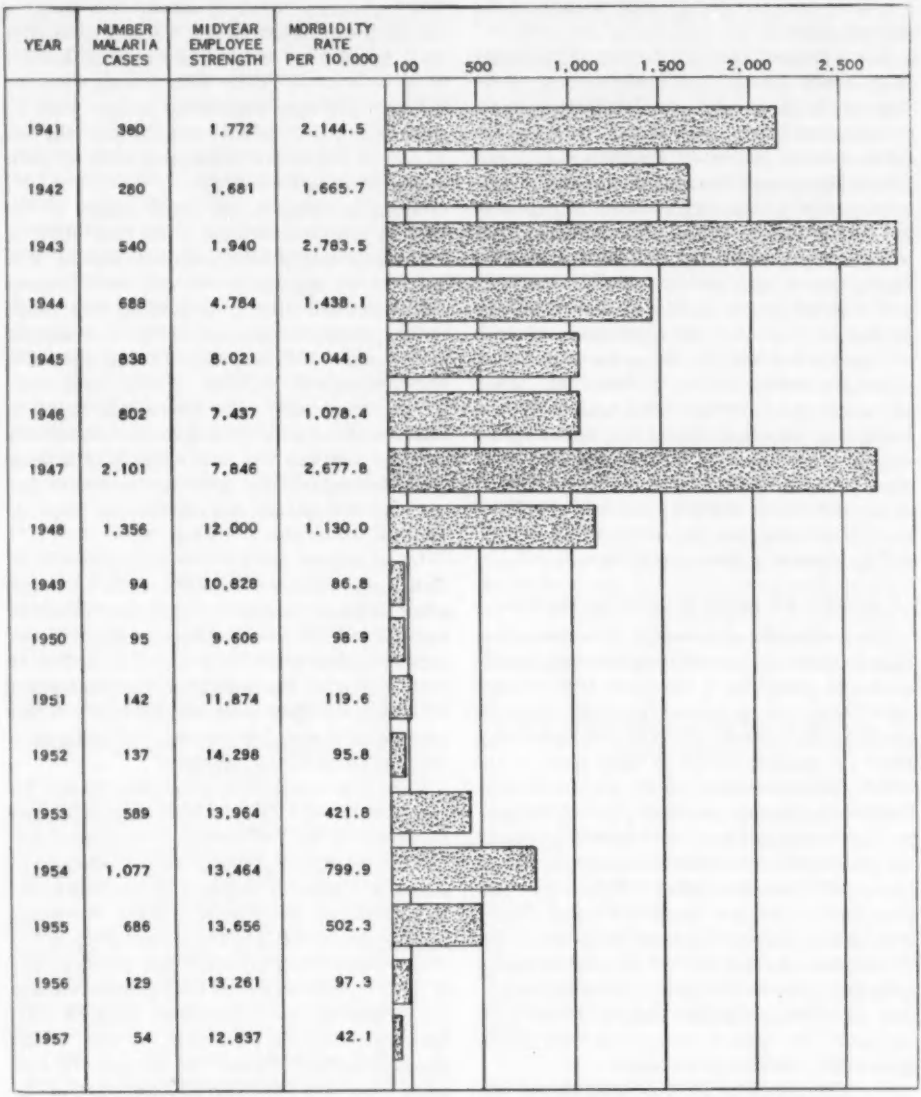

FIG. 20. Annual malaria morbidity rates in Aramco Saudi Arab employees, 1941–1957

pleted in November. A recommended earlier starting date had to be delayed pending arrival of needed equipment and insecticides. In spite of these delays, Aramco morbidity rates for November and December declined to 22 and 20/10,000, the lowest monthly rates recorded up to this date.

Our November, 1948, parasite surveys for the entire Qatif oasis showed a decline from 84.8 per cent to 51.9 per cent, the overall infant parasite rate from 100 per cent to 44.4 per cent. On nearby untreated Tarut Island, Tarut village continued to show a parasite rate of 85.8 per cent and an

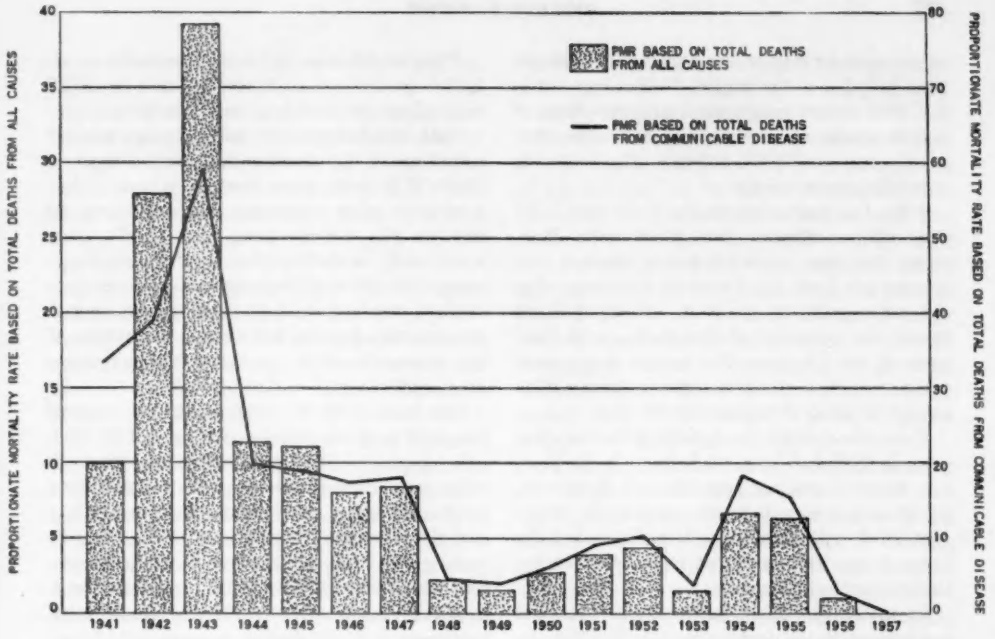

FIG. 21. Proportionate malaria mortality rates based on deaths in Aramco hospitals, all age groups, excluding newborns, 1941–1957

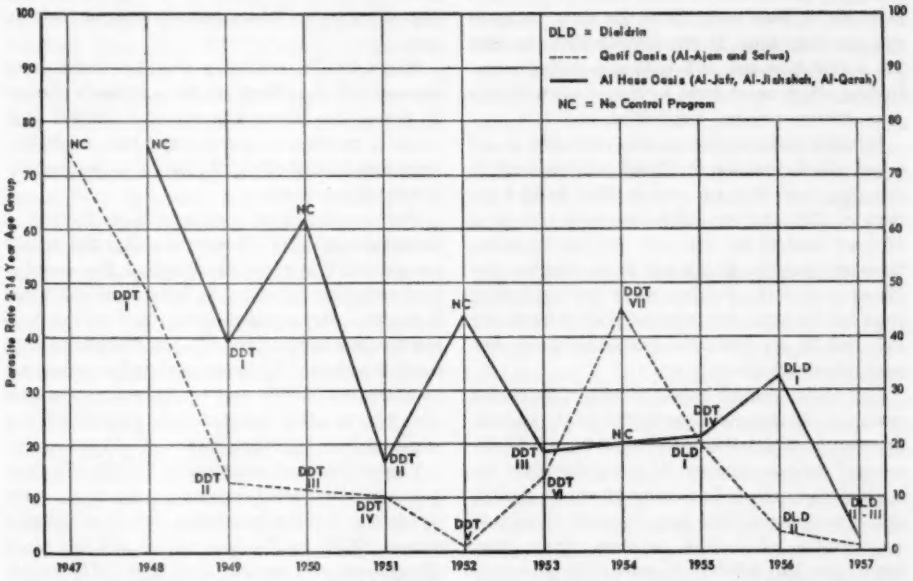

FIG. 22. Annual versus biennial residual spray treatments in malaria control, Qatif and al-Hasa oases, 1947–1957

infant parasite rate of 100 per cent. (It had not been included in the original 1947 survey nor in the 1948 control program). Thus, the effects of only 2 months of residual action seemed to show great promise of DDT's potential effectiveness in controlling oasis malaria.

1949. The impressive results of the first DDT application continued throughout 1949. Relatively few cases occurred among Aramco employees (see Table 22); and most of the cases that did occur could be traced to untreated Tarut Island, the untreated al-Hasa oasis, or to other parts of the Kingdom. The normal spring peak was represented by only a slight increase in May rates over those of neighboring months.

Recommendations for repeating the fall program in 1949 had been made early in the year, but approval was not granted until November. Spray operations were begun immediately, 50 per cent DDT wettable powder being used; but the program was not completed until well past the peak transmission season.

In spite of the delay, fall morbidity rates did not increase to the degree expected. The November peak rate was only 19/10,000. Of the 18 Saudi Arab employee cases reported in that month, 13 could be traced to as-yet-unsprayed Tarut Island or to the al-Hasa oasis where the spray program was just beginning. It was obvious that the 1948 fall application was still having a definite controlling effect on malaria incidence more than a year after its original application.

Parasite rates confirmed this extension of residual effect; that for the Qatif oasis as a whole dropping from 51.9 per cent in 1948 to 14.4 per cent in 1949 and the infant parasite rate from 44.4 per cent to 3.3 per cent. *Falciparum* infections continued to decline and accounted for only 12 per cent of the positives while the long-lasting *vivax* and *malariae* infections accounted for 64 per cent and 20 per cent. The remaining 4 per cent were mixed infections.

Our entomological checks during this period confirmed the unusual longevity of DDT residues. The first anopheline to be collected from a DDT-sprayed surface appeared 11.5 months after the original application. In a 13 to 14-month period, only 2 to 6 anophelines were found in 15-minute examinations of treated premises. Even these might have had a lethal exposure if 24-hour mortalities had been observed. By contrast, 103 to 120 anophelines per 15-minute catch were being obtained in nearby untreated check shelters.

Thus, all evidence at this time indicated an effective control of more than 12 months for DDT residual sprays under local oasis conditions.

1950. The delayed 1949 fall campaign was not completed in the al-Hasa oasis until February, 1950. With both oases treated, extremely low morbidity rates continued over the first 10 months. The normal spring peak of May-June could hardly be distinguished. Of the 14 employee cases that did occur between January and September, over half could be traced to non-treated communities. For the first time in the history of the Aramco hospitals, no Saudi Arab employee cases were recorded in April and July.

The Saudi Arab Government did not approve the joint program proposed for the fall of 1950, and no general DDT application was made in either oasis. However, the program was continued by Aramco on an experimental basis in al-Ajam and Safwa where 75 per cent DDT wettable powder was used for the first time (previously only 50 per cent DDT wettable powder had been available). In these treated villages, parasite rates continued a slight decline, averaging 11.7 per cent, but the infant parasite rate rose from 0 to 9 per cent. In untreated Qatif villages, the composite parasite rate rose to 56.7 per cent (see Fig. 22) with an infant parasite rate of 35.5 per cent.

November-December morbidity rates now showed definite effects of the program's discontinuance. The November rate of 37/10,000 indicated a possible failure to maintain as high a degree of control after 10 months as we had experienced previously.

Our entomological evidence also showed a shortened period of effectiveness after the second annual DDT application. The first few anophelines returning to treated surfaces were now noted 5 months after application instead of the 11.5 months previously observed. Again numbers were small (5 to 6 per 15-minute catch) when compared to untreated checks, and no 24-hour mortalities were run to see if a lethal dose were still being acquired from the deposits.

This evidence of reduction in DDT's effectiveness caused no great concern at this time, since we felt our recommendation for a well-timed annual DDT application would still maintain effective malaria control. Although DDT resistance in house flies had been experienced, no account of such resistance in any anopheline had yet been noted. Hence, our major effort was

directed toward achieving a carefully timed annual schedule of DDT applications to obtain effective control. In retrospect, it would have been of special interest if careful laboratory investigations on resistance could have been devised at this time; so that an early series of such studies could have been initiated on a problem which is now of major concern to malariologists throughout the world.

1951. Even though no DDT was applied in 1950, malaria morbidity remained fairly low throughout the year. The spring peak was made evident through a relatively sharp increase in May morbidity, and November rates climbed to 46.6/10,000 (Table 22).

DDT residual-spray programs were approved for both oases, but delays in receiving supplies were reflected in a postoptimum spraying schedule in November and early December. This delay in application explained the relatively high November rate, but December and January morbidities quickly declined to reflect the apparent effectiveness of DDT in checking transmission.

Surveys showed another slight decline in parasite rate to 10.5 per cent in the experimental villages of al-Ajam and Safwa sprayed annually since 1948, but the infant parasite rate remained about the same, 9.7 per cent. Villages which had not been sprayed in 1950 responded to the 1951 fall application by a parallel decline in parasite rate from 56.7 per cent to 29.7 per cent (see Fig. 22), and the infant parasite rate dropped from 35.5 per cent back to 8.0 per cent.

No entomological evidence of obvious DDT failure was apparent, and all available information pointed to effective malaria control if recommended annual spraying schedules could be met. In spite of shortened DDT effectiveness, we felt that September applications would protect over the fall and spring transmission seasons; and the hot, dry, summer months would continue this protection until residues could be reapplied the following September.

1952. Throughout the year, malaria morbidity remained at a low level, reflecting the success of the fall, 1951, campaigns in both oases. The fall, 1952, spray program was approved for the Qatif area only, but even this program was not carried out until November because of administrative delays in negotiation of a joint agreement between the Company and the Government. November morbidity rates increased to 62.4/10,000, but this increase seemed adequately explained by the delayed DDT application. This explanation was apparently confirmed by a sharp drop in December rates to 10.1/10,000.

Parasite rates in our two experimental villages (al-Ajam and Safwa) dropped to an all time low of 1.0 per cent but the infant parasite rate had increased from 9.7 per cent to 18.2 per cent. The parasite rate for the entire Qatif oasis averaged 18.8 per cent; this was a slight reduction from a general rate of 20.6 per cent recorded the previous fall. In spite of the unusual increase in infant parasite rate in Safwa and al-Ajam, that for the other Qatif villages remained low, 3.8 per cent. With no other evidence to the contrary, we assumed that DDT was still giving adequate malaria control throughout 1952.

Of special interest was the establishment of several observation stations in the Qatif oasis during the year to look for any evidence of DDT resistance in local *stephensi* in view of the first reports of DDT resistance in anophelines in Greece. No such evidence was noted in 1952.

1953. The fall, 1952, DDT deposit continued to give effective anopheline control throughout the year, and no mosquitoes were found in treated houses up to the time of the general respraying of both oases in the fall of 1953. Our entomological observations up to this time gave no hint of developing DDT resistance. Unfortunately, our entomologist resigned; and no check observations were available for the postspray period in late 1953 and most of 1954. In retrospect, this proved most unfortunate, since entomological data through this critical period might have given us adequate advance warning of increased malaria morbidity in November and December.

November rates reached the highest level recorded in our postcontrol years, 330.8/10,000. Parasite rates in al-Ajam and Safwa rose from 1.0 per cent to 14.4 per cent; the infant rate, from 18.2 per cent to 27.8 per cent. The general parasite rate for the Qatif oasis as a whole remained about the same, 18.2%, but the infant parasite rate rose from 8.1 per cent to 12.5 per cent. Again, late applications of insecticide in November and December were thought to explain these increases at the time. But, judging from subsequent events, these increases may have represented early malariometric evidence for DDT resistance which became more marked in the following year.

1954. In spite of the 1953 DDT applications, 1954 monthly morbidity rates were consistently

higher than they had ever been since control measures were initiated in 1948 (see Table 22); and the 1954 annual rate (772/10,000) was approaching that of precontrol years. Hence, every effort was made to apply DDT residues early enough for maximum effect. DDT residual applications began in August in the Qatif oasis, but the al-Hasa program was not approved until spring 1955. Experimental lots of dieldrin had been obtained, and a number of different test houses utilizing different dieldrin dosages were set up at the same time for observation and comparisons with DDT.

Unfortunately, no entomological observations had been made since the fall of 1953 since we were without the services of an entomologist, and the writer was placed on special administrative assignment. With recruitment of a new entomologist, observations on vector reaction to DDT and dieldrin were reinstituted after a lapse of 1 year.

In October, only a few weeks after DDT application, *stephensi* began to reappear in treated houses. With the above gap in observations, this constituted our first, definite, entomological evidence of DDT failure in the Qatif oasis. In November and December this became more obvious, and anophelines were numerous in recently sprayed houses. By contrast, during this same period, experimental shelters treated with dieldrin were anopheline-free.

This failure to control anophelines was reflected in the high November-December morbidity rates (311 and 130/10,000) and was confirmed by November parasite surveys in oasis villages. The parasite rate in al-Ajam and Safwa rose sharply from 14.4 per cent in 1953 to 44.9 per cent in 1954 (see Fig. 23) with an infant parasite rate of 31.3 per cent. In the Qatif oasis generally, the rate rose from 18.2 per cent to 41.5 per cent; the infant parasite rate from 12.5 per cent to 32.4 per cent. Thus, by the end of 1954, morbidity data, parasite rates, transmission indices, and entomological observations all pointed to DDT's failure to control malaria effectively.

1955. Malariometric evidence accumulating during the early part of 1955 (see Table 22) more than confirmed our previous fears. Monthly morbidity rates were even higher than in 1954, and *stephensi* continued to be reported from DDT-treated shelters. With anopheline resistance to DDT being reported in Greece, Lebanon, Java, and United States, a cable was sent to the World Health Organization (April, 1955) informing them of our belief that *Anopheles stephensi* had also developed resistance to DDT in Saudi Arabia and that DDT would be replaced with dieldrin in future residual-spray programs.

Residual-spray operations in al-Hasa using DDT (the only locally available insecticide) had already begun by February. In April, these supplies were exhausted, and in May, newly-received dieldrin was used to complete the program in the remaining al-Hasa villages.

The 1955 fall spray program in Qatif began in August with dieldrin being used for the first time in an oasis-wide program. Most of the Qatif oasis was treated by September; Tarut Island, Dammam and al-Khobar by mid-October.

Entomological checks showed no anophelines in premises newly treated with dieldrin, and even anopheline larvae were extremely difficult to find in the Qatif area after dieldrin had been widely used. This general decrease in larval population had not been observed where DDT was used in previous area-wide programs.

Morbidity rates during the fall months of 1955 dropped sharply from comparable 1954 rates (see Table 22). More than half of the cases reported were traced to DDT-treated al-Hasa villages.

Our November malaria survey reflected this trend. Al-Ajam and Safwa showed a composite parasite rate of 19.8 per cent; a sharp drop from 44.9 per cent recorded in 1954. The infant parasite rate in these two villages dropped from 31.3 per cent to 6.7 per cent. The parasite rate for the entire Qatif oasis was 31.4 per cent as compared with 41.5 per cent the previous year while the comparable infant parasite rate dropped from 32.4 per cent to 7.7 per cent.

1956. Morbidity rates continued at a very low level during all of 1956, the usual seasonal rises in spring and fall being almost entirely obliterated (see Table 22). This, plus the overwhelming preponderance of *vivax* (82.9%) over *falciparum* infections (15.5%), indicated that many of the cases that did occur probably represented clinical relapses and not new infections. This trend had started after the close of the spring transmission season in 1955.

Fall parasite surveys in al-Ajam and Safwa showed a further decline from 19.8 per cent in 1955 to 3.6 per cent in 1956, and composite rates for the entire Qatif oasis dropped from 31.4 per cent to 12.5 per cent in 1956. For the first time on record, the infant parasite rates in both experi-

mental villages and the Qatif oasis as a whole were 0 per cent; indicating complete stoppage of malaria transmission!

1957. Monthly morbidity declined even further after both oases had been treated with dieldrin in the fall of 1956. Only 54 cases were reported in Aramco Saudi Arab employees for the entire year; an annual rate of 42.0/10,000; the lowest ever recorded for the Aramco employee group. The November rate was also the lowest ever recorded (3.1/10,000) for this normally peak month, and only one employee case was reported in December.

Again, no seasonal peaks were evident, and *vivax* cases (88.9%) were even more predominant than in 1956. Only five *falciparum* (9.2%) and one *malariae* case (1.9%) were reported for the year in addition to the 48 *vivax* infections in 12,837 Saudi Arab employees (the midyear employee population). Again, the nonseasonal distribution of cases and the rare occurrence of *falciparum* infections meant that the few cases that did occur during the year may have been largely due to relapses and not to new infections. For the first year on record, no malaria deaths in any population group were reported from Aramco hospitals.

Although entomological checks showed a few *stephensi* could be collected in dieldrin-sprayed areas in May, the mosquitoes were present in very small numbers. No 24-hour mortalities were observed to see if even these few adult *stephensi* were still receiving a lethal dose. After respraying with dieldrin in the fall of 1957, *stephensi* again became extremely rare, both larvae and adults being difficult to find.

Village surveys in the fall reflected the sharp decline in malaria morbidity. In al-Ajam and Safwa, the parasite rate was 1.4 per cent. The three positive films discovered in these two villages were all very light *malariae* infections, one in the same individual reported as a *malariae* infection in 1956. The general parasite rate for the Qatif oasis (excluding Tarut) was 6.4 per cent; that for al-Hasa, 2.7 per cent. For the second successive year, the infant parasite rate in the

TABLE 25

Pre-control and post-control village survey data as a measure of malaria control with residual sprays 1947–48 and 1957

Town	Survey date	Infant parasite rate	Number children examined*	Parasite rate	Spleen rate	Aggregate malaria index	Average spleen	Average enlarged spleen	Spleno-metric index
Qatif Oasis									
Al-Ajam	Dec. 1, 1947	No data	84	77.4%	91.7%	95.2%	2.2	2.4	220.1
	Nov. 23, 1957	*0.0%*	*117*	*0.9*	*1.7*	*2.6*	*0.02*	*1.0*	*1.7*
'Anik	Nov. 30, 1947	100.0	54	98.1	98.1	100.0	2.6	2.6	255.1
	Nov. 25, 1957	*0.0*	*87*	*17.2*	*4.6*	*18.4*	*0.08*	*1.8*	*8.3*
Qatif	Dec. 9, 1947	No data	52	90.4	98.1	100.0	1.8	1.9	186.4
	Nov. 25, 1957	*0.0*	*116*	*3.4*	*4.3*	*7.8*	*0.04*	*1.0*	*4.3*
Safwa	Dec. 14, 1947	No data	98	71.4	96.9	99.0	1.8	1.9	184.1
	Nov. 23, 1957	*0.0*	*100*	*2.0*	*1.0*	*3.0*	*0.01*	*1.0*	*1.0*
Saihat	Nov. 26, 1947	100.0	121	92.6	90.9	99.2	2.4	2.7	245.4
	Nov. 25, 1957	*0.0*	*112*	*10.7*	*7.1*	*17.0*	*0.1*	*1.5*	*10.7*
Tarut†	Nov. 24, 1948	100.0	127	85.8	51.2	91.3	1.2	2.4	122.9
	Nov. 27, 1957	*0.0*	*83*	*12.0*	*16.9*	*27.7*	*0.2*	*1.2*	*20.5*
Al-Hasa Oasis									
Al-Jafr	Nov. 29, 1948	No data	29	82.8	48.3	82.8	1.2	2.5	120.8
	Nov. 19, 1957	*0.0*	*91*	*4.4*	*33.0*	*36.3*	*0.4*	*1.3*	*42.9*
Al-Jishshah	Nov. 29, 1948	No data	42	31.0	26.2	47.6	0.7	2.5	62.5
	Nov. 19, 1957	*0.0*	*96*	*1.0*	*21.9*	*21.9*	*0.3*	*1.2*	*26.3*
Al-Qarah	Nov. 30, 1948	100.0%	68	100.0	42.6	100.0	1.1	2.5	106.5
	Nov. 20, 1957	*0.0*	*73*	*2.7*	*20.5*	*24.7*	*0.2*	*1.1*	*22.6*

* 2–14 year age group.

† Only village unsprayed prior to fall 1957 survey.

Qatif oasis as a whole was 0 per cent. In al-Hasa as well, the transmission index was nil in 1957. These data indicate practical cessation of malaria transmission in both the Qatif and al-Hasa oases by the end of 1957.

1958. Morbidity data showed a continued decline throughout 1958 (Table 22), the 1958 annual rate being 28.3/10,000. This is the lowest employee malaria rate in the history of Aramco's Medical Department.

RESUMÉ OF SUCCESSFUL MALARIA CONTROL WITH RESIDUAL SPRAYS

In spite of the failure of DDT to control malaria adequately in the years 1953 through 1955, the residual-spray technique alone has proved entirely successful in oasis-malaria control up to the present. With dieldrin as the insecticide of choice, malaria transmission had been stopped, for all practical purposes, by the end of 1957. This was reflected in the absence of malaria mortality in Aramco hospitals during that year, in the low annual and fall seasonal morbidity, zero transmission indices in both oases, and extremely low parasite rates in the 1957 fall surveys in the villages.

A summary of "before and after" conditions in Qatif and al-Hasa villages is presented in Table 25. The various criteria of measurement presented in this table emphasize the paramount importance of malaria as a public health problem in these oases up to 1948–1949 as well as the extent to which this problem was reduced by 1957 utilizing the residual spray technique, with dieldrin as the residual insecticide.

Where patients with malaria have reported for treatment or where parasitemia has been discovered, *vivax* and *malariae* have been almost wholly responsible. Of the 1,058 children examined in 1957 in both oases, 56 were found to have positive blood films. Of these, 32 were *malariae* and 24 *falciparum*. Since *malariae* (in children) and *vivax* infections (in adults) could readily represent relapses rather than new infections, the success of dieldrin in local malaria control is perhaps even greater than currently low morbidity and low parasitemia indicate. The lack of mortality and complete prevention of transmission indicated by zero infant parasite rates are a better reflection of dieldrin's potential value in the residual spray technique.

PART VI. DEVELOPMENT OF DDT RESISTANCE IN *ANOPHELES STEPHENSI* AND RESUMPTION OF CONTROL WITH DIELDRIN

During the first year's application of DDT, no *stephensi* were found resting on sprayed surfaces until 12 months after treatment. Even then, numbers were very small; and effective malaria control probably extended well beyond this 12-month period. Monthly malaria-morbidity rates continued at low levels from the fall of 1948 through the next several years in spite of occasional lapses in the annual program or delays past the recommended time of application. The few, slightly higher, November peaks that did occur were explained by these delays or by these lapses in treatment. There seemed no doubt at the time, therefore, that a single annual application of DDT applied in August-September would be more than adequate in oasis malaria control under local conditions.

This general opinion prevailed until the fall of 1953 and early 1954. In November, 1953, the monthly morbidity rate reached an alarming 331/10,000; higher than had ever been recorded since control measures began. The fact that the fall application was delayed beyond the recommended date (actually it was underway at the same time) plus the fact that the al-Hasa oasis had not been included in the 1952 program the previous year, were thought to be a possible explanation of this unusual increase at the time. Our main conclusion was to re-emphasize the need for annual treatment and more accurate timing of annual applications in August-September. This increase in morbidity, we thought then, was primarily a lesson in timing.

When the monthly malaria rates continued at a higher level throughout 1954 in spite of both oases being sprayed with DDT, our uneasiness increased. Small quantities of dieldrin were being tested along with preparations for well-timed DDT applications to be made in the fall of 1954. With 9-month delivery schedules for the quantities of insecticides needed in these large-scale programs, only DDT was available for the fall,

1954, application. Emphasis on proper timing enabled the Qatif program to be completed in August and September. The al-Hasa oasis was not approved by the Saudi Arab government for inclusion in the joint 1954 program (spraying delayed until spring 1955).

Our first warning of what was to happen was the reappearance of *stephensi* in numbers in treated houses only a few weeks after the 1954 DDT spray application was completed. In 1948, 12 to 14 months had elapsed before our first *stephensi* were collected on sprayed surfaces. In 1954, they were reappearing in numbers within a few weeks of treatment.

Our fall malaria peak began climbing in October. In November, it reached 311/10,000, the same high level as the previous year. Late application of insecticide failed to account for the increase this time. But the lack of a program in the al-Hasa oasis that fall still offered a partial explanation.

Any doubts about DDT's possible failure to control malaria were dispelled, however, when the results of our 1954 November survey in the villages became available. In every village, parasite and spleen rates had increased alarmingly; even in our experimental villages where *annual* DDT applications had been made each fall from 1948 through 1954 (see Fig. 23). This increase in November parasite rates in the villages paralleled our November morbidity increase (see Table 22).

With these experiences in DDT failure in the fall of 1954, we were not surprised to find consistently higher monthly morbidity rates in early 1955. By this time we felt no doubt that DDT resistance was responsible for this failure in malaria control, and plans were made to replace DDT with dieldrin in the coming fall, 1955, residual spray campaign.

Dieldrin was used on an oasis-wide scale in Qatif for the first time in the fall of 1955. Al-Hasa had been treated the previous spring at Saudi Arab Government request with the DDT still available. The first shipments of dieldrin began to arrive in May, 1955, and the few villages yet to be sprayed in al-Hasa were treated with dieldrin at that time.

After this first wide-scale use of dieldrin, a general decline in morbidity, mortality, spleen and parasite rates began. When the dieldrin program was repeated in the fall of 1956 and again in 1957 by the Ministry of Health, the rates continued to decline, and have since reached levels comparable to, or lower than, our best DDT years. This decline has continued up to the present (see Table 22 and Fig. 24).

Similar experiences in DDT resistance in *stephensi* have since been reported in other parts of the Persian Gulf area and in India, even though Pal *et al.*, (1952) had unsuccessfully attempted the development of a resistant *stephensi* strain previously by exposure of adults to sublethal dosages (12.5 mg/sq ft). Rajagopalan, Vedamanikkam, and Ramoo (1956) noted DDT resistance in *stephensi* larvae in south India. Davidson *et al.*, (1957) and Davidson (1958) have since reported the development of some degree of DDT resistance in *stephensi* after exposure of laboratory colonies to sublethal dosages over a 2-year period. The degree of resistance was said to be much less than that observed in naturally resistant populations in Saudi Arabia.

Within the Persian Gulf area, Gramiccia *et al.*, (1957) have reported DDT resistance in *stephensi* from southern Iraq near Abadan. DDT larviciding had been practiced irregularly since 1947 and imagiciding since 1954. More recently, Mofidi and coworkers (1958 a and b) report similar resistance in adjacent southern Iran. In some areas, this resistance was associated with 1957 fall outbreaks of malaria; in others, no such increase was noted. In all these previous observations on *stephensi*-resistance to DDT, no details are given as to actual effects on malaria incidence.

MALARIOMETRIC EVIDENCE

Our own best malariometric evidence to support our general account of DDT resistance development in Saudi Arabia comes from the two experimental villages of al-Ajam and Safwa in the Qatif oasis (see Fig. 23). These two villages are the only ones in our study area that have received annual fall applications of residual insecticides from 1947 to the present (1958). DDT was used from 1948 through 1954, dieldrin from 1955 through 1958. Annual November parasite surveys have also been made to follow the effects of these applications on malaria control. The remarkable correlation between effects on November parasite rates in these two experimental villages and annual morbidity rates for the Province as a whole is shown in Fig. 24. From this we feel that malariological events in the two

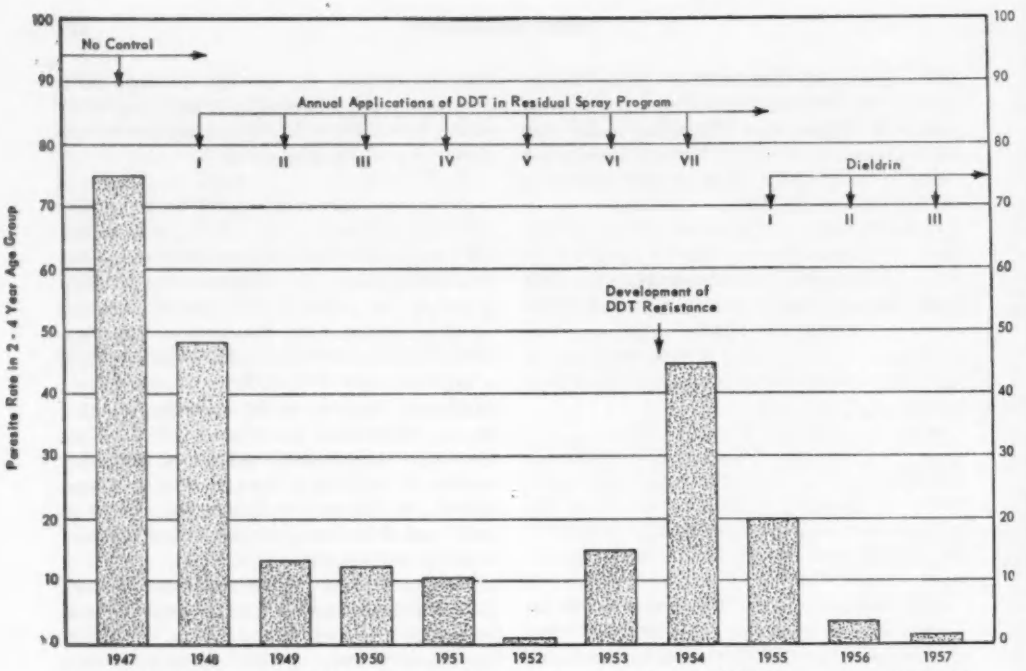

FIG. 23. Development of DDT resistance and resumption of control by dieldrin, experimental Qatif oasis villages, al-Ajam and Safwa, 1947–1957

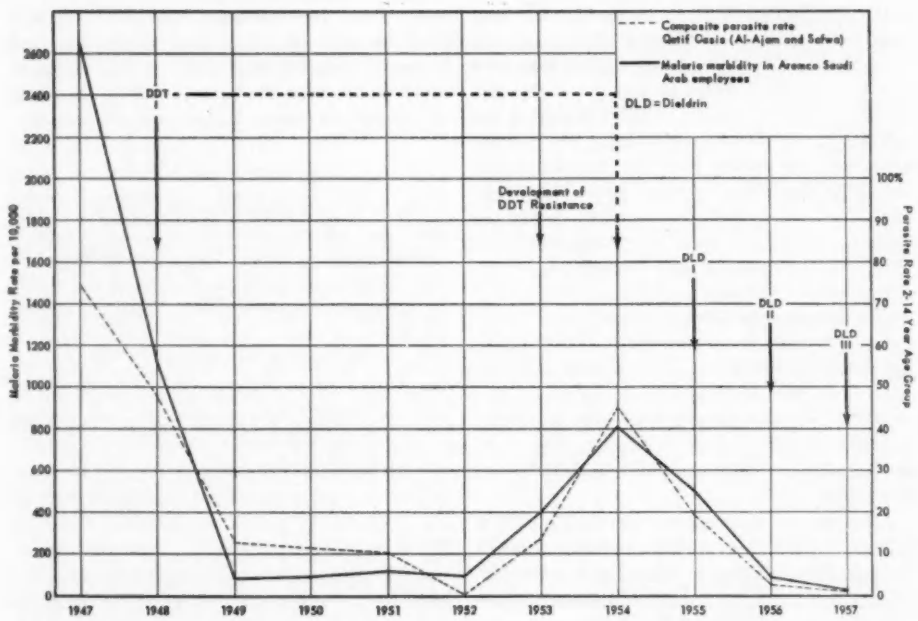

FIG. 24. Malariometric evidence for development of DDT resistance, Qatif oasis, 1947–1957

experimental villages reflect those in the Qatif oasis as a whole during this period.

Both illustrations (Figs. 23–24) show the success of DDT in controlling malaria in the years 1949 through 1952, the beginning of failure in late 1953, and the great increase both in parasitemia and morbidity in 1954 in spite of well-timed DDT applications. This is ascribed to DDT resistance in *Anopheles stephensi*. With the advent of dieldrin (first wide-scale use in Qatif in 1955, in al-Hasa in 1956), both rates began a parallel decline in 1955, and have reached all-time lows in 1957. This, we feel, confirms DDT resistance as the true explanation for failure to control malaria in late 1953 and 1954.

More detailed malariometric evidence for development of resistance to DDT and resumption of effective malaria control by dieldrin in these experimental villages is given in Table 26. Although numbers of observations are small, the parallel increase in infant parasite rates and 2- to 14-year parasite rates in 1953 and 1954 are good evidence of DDT failure to control malaria transmission. Their subsequent decline in 1955, 1956 and 1957 with use of dieldrin emphasizes the improved effectiveness of dieldrin over DDT in local residual-spray programs. In 1956, and again in 1957, the transmission index (infant parasite rate) in these two villages was zero; further proof of dieldrin's continued effectiveness.

A preponderance of *falciparum* positives (85%) over *vivax* (10%) is noted with an increased infant parasite rate in November, 1953. When pre-control parasite formulas are considered, this can be taken as evidence of active transmission and many new infections. Presumably, DDT resistance must have been active at least by October, 1953, to give these results. Careful examination of infant parasite rates and the more-than-usual preponderance of *falciparum* over *vivax* from 1950 through 1953 makes one suspicious that such resistance was beginning to make itself felt in these villages after the third DDT application in 1950. But the small numbers of observations involved plus the very low parasite rate in 1952 make this suspicion difficult to substantiate.

The early success of DDT in controlling morbidity, the increase in morbidity in 1953–54 with DDT resistance, and the new decline with use of dieldrin in 1955 through 58 have been summarized in Figures 20 and 24 and in Tables 22 and 26. Comparable fluctuations in malaria mortality are shown in Figure 21. Of special interest in this connection is the relative importance of the different parasite species responsible for malaria infec-

TABLE 26

Changes in parasitemia and parasite formula with annual residual sprays in al-Ajam and Safwa, 1947–1957
Qatif Oasis

Year	Infants		Two-fourteen year age group											
	Infant parasite rate		Parasite Rate		Vivax		Falciparum		Malariae		Unidentified		Mixed	
	Number examined	Per cent	Number examined	Per cent	Number positive	Per cent	Number positive	Per cent	Number positive	Per cent	Number positive	Per cent	Number positive	Per cent
1947	(11*)	(100.0*)	182	74.2	63	46.7	46	34.1	16	11.9	4	3.0	6	4.4
1948	10†	30.0	132	47.7	36	57.1	15	23.8	8	12.7			4	6.3
1949	48	0	106	13.2	9	64.3	1	7.1	3	21.4			1	7.1
1950	11	9.1	179	11.7	5	23.8	16	76.2						
1951	31	9.7	133	10.5	1	7.1	12	85.7	1	7.1				
1952	11	18.2	99	1.0							1	100.0		
1953	18†	27.8	139	14.4	2	10.0	17	85.0					1	5.0
1954	64†	31.3	107	44.9	17	35.4	27	56.3	1	2.1	1	2.1	2	4.2
1955	15	6.7	182	19.8	17	47.2	13	36.1	5	13.9			1	2.8
1956	21	0	221	3.6	2	25.0	2	25.0	4	50.0				
1957	18	0	217	1.4					3	100.0				

* No data available from Al-Ajam and Safwa in 1947, 100% infant parasite rate from other Qatif Oasis villages.

† May include some 12–23 month infants as well as 0–11 month group.

tions in Aramco employees during these same years of developing DDT resistance. These data are shown in Table 27.

CHANGES IN PARASITE FORMULA

In our original village surveys (Table 13) before control measures were attempted, *falciparum* and *vivax* infections were almost equal in frequency, with *falciparum* slightly predominant. This ratio is thus assumed to be the normal parasite formula when uncontrolled transmission occurs in this area. This same *falciparum*:*vivax* ratio appeared in an analysis of Aramco-employee morbidity in 1953 (Table 27). In 1954, the ratio was about equal. Thus, both increasing numbers of cases as well as parasite ratios indicated that transmission was active in spite of DDT control attempts in these years.

By contrast, when dieldrin was introduced in 1955, *vivax* became relatively more abundant and has increased its predominance over *falciparum* each year through 1957. Many of these *vivax* infections probably represent relapses of predieldrin infections. As employee infections continue to be treated or disappear naturally, we can expect further decline in overall morbidity and almost complete absence of local *falciparum* infections in the next few years, unless resistance to dieldrin develops.

In the village children (who rarely if ever receive treatment for malaria) *falciparum* has also lost its predominance through 1957 (see Table 26). *Vivax* has become predominant, and more recently has given way to *malariae* as the most commonly encountered species causing parasitemia. This trend also dates from the first dieldrin application in 1955. The zero infant parasite rates, together with this change in parasite formula, are further evidence of rapidly declining malaria transmission once DDT resistance was overcome by replacement with dieldrin.

The *malariae* infections now predominant in village parasitemia probably represent predieldrin infections. To emphasize this point, one of the three *malariae* infections in al-Ajam and Safwa in 1957 was also reported in 1956 in the same individual. In all these current *malariae* infections, parasites are very sparse in the blood films; another indication of age of the infection and status of immunity development.

FIELD ENTOMOLOGICAL EVIDENCE FOR DDT RESISTANCE

Entomological observations on the length of residual effectiveness of DDT were begun in 1947 and were continued in certain test houses in the Qatif oasis in 1948 at the time of the first general DDT applications in the oasis. These consisted of 15-minute collections of resting mosquitoes in selected treated and check shelters, but none of these collections was held to determine possible mortality at the end of 24 hours. Observations on the normal, expected, seasonal fluctuations in anopheline density had already been made in 1947, over a year previous to the first annual DDT program. These observations are summar-

TABLE 27

Variations in species of parasite responsible for malaria morbidity in Saudi Arab employees, Arabian American Oil Company, 1947–1957

Year	Cases	Vivax (%)		Falciparum (%)		Malariae (%)		Mixed (%)		Undetermined (%)	
1947	2,101	5.8	(121)	30.3	(637)					63.9	(1,343)
1948	1,356	10.2	(138)	17.2	(233)	1.2	(16)			71.5	(969)
1949	94	55.3	(52)	18.1	(17)			2.1	(2)	24.5	(23)
1950	95	32.6	(31)	49.5	(47)	11.6	(11)	6.3	(6)		
1951	142	16.2	(23)	69.0	(98)	4.2	(6)	8.5	(12)	2.1	(3)
1952	137	13.9	(19)	82.5	(113)	1.5	(2)	2.2	(3)		
1953	589	41.6	(245)	53.5	(315)	0.3	(2)	4.2	(25)	0.3	(2)
1954	1,077	49.9	(537)	47.4	(511)	0.2	(2)	1.7	(18)	0.8	(9)
1955	686	63.6	(436)	35.4	(243)			1.0	(7)		
1956	129	82.9	(107)	15.5	(20)			1.6	(2)		
1957	54	88.9	(48)	9.2	(5)	1.9	(1)				
Total.....	6,460	27.2	(1,757)	34.7	(2,239)	0.6	(40)	1.2	(75)	36.4	(2,349)

ized in Figure 13 and can be used in evaluating the changes due to insecticidal treatment.

Through the period October, 1947–October, 1948, seasonal collections of anophelines were made in a garden barasti just south of the village of Qatif. In general, anopheline densities followed the same pattern found in the Saihat barasti outlined in Figure 13. This Qatif "test house" was first sprayed with 5 per cent DDT in kerosene in late October, 1948. Subsequent 15-minute checks for adults made semimonthly showed no mosquitoes until almost a year later (August 15, 1949) when a single anopheline was seen resting on the previously-sprayed surface. It escaped collection. None was found again until 1 month later when two were seen on September 15, 1949, resting on dark clothing hung in the sprayed room. None was actually found on the sprayed walls up to this time. On October 18, 1949, six *stephensi* were found on the sprayed surfaces. Two were collected November 10, five on November 15, and six on December 19; all *stephensi*. The building was resprayed at this time. During this same period as many as 300 adult anophelines could be collected in unsprayed barastis nearby, indicating considerable control by DDT residues even though mosquitoes were beginning to reappear. No 24-hour mortalities were determined, hence we are unable to state whether or not these individuals were still receiving a lethal dose or whether or not they would have lived long enough to transmit if they had been infected.

From these data, the first anophelines (other than the single specimen sighted August 15th and the two on clothing, September 15, 1949) collected from DDT-treated surfaces were found 11.5 months after the initial 5 per cent DDT in kerosene was applied at approximately 200 mg/sq ft. In the experimental shelter at Saihat, treated with 2.5% DDT suspension to obtain the same dosage, the first adults were found 12 months after application.

In the following year, after the second annual application of DDT suspension, seven specimens of *stephensi* were found 5 months after application (May 5, 1950). These collection data, along with observations on an untreated check shelter, are summarized in Table 28. Hence, even in the second year after the second annual DDT application, some evidence was becoming apparent that the length of residual effectiveness (as measured by reappearance of *stephensi* on sprayed surfaces) was declining. No effects on malaria morbidity were observed at that time. In retrospect, however, this is additional confirmation of the suspected beginning of decreased effectiveness referred to in the discussion of Table 26.

TABLE 28

Anophelines collected in treated and untreated shelters (Qatif Oasis), 1948–1950 (15-minute catches)

Date	No. of *Anopheles* found		
	2.5% D.D.T. suspension (Saihat)	5% D.D.T.-kerosene (Qatif)	Untreated control (North Saihat)
Oct. 11, 1948	199	200	
Oct. 15	Sprayed DDT I Oct., 1948	Sprayed DDT I Oct., 1948	
No Anopheles found until:			
Oct. 18, 1949	3*	6†	88
Oct. 24			276
Oct. 25	3		302
Nov. 4	2	0	74
Nov. 10	0	2	117
Nov. 15	1	5	105
Dec. 19	Resprayed DDT II Suspension Dec., 1949	Resprayed DDT II Suspension Dec., 1949	
No *Anopheles found until:*			
Jan 10, 1950			57
May 5		7‡	
May 15		6	
June 23		0	
July 19		5	

* After 12 mo. interval.
† After 11.5 mo. interval.
‡ After 5 mo. interval.

Observations on the return of *stephensi* to shelters 2 months after the 1954 application and throughout 1955 have already been emphasized. By this time, other evidence of DDT resistance had been accumulating and this only confirmed our impressions of resistance development.

During the year 1956, observations on the return of anophelines to 1955 dieldrin- and DDT-treated houses were continued. In the al-Hasa oasis, most of the garden villages were treated in the spring of 1955 with DDT, a few (al-Qarah, al-Battaliyah, and al-'Umran) being reserved for

early trials with dieldrin. Although a few *stephensi* began to appear after 3 to 4 months in houses reportedly sprayed with dieldrin (no 24-hour mortality observations), the numbers in DDT-treated houses far surpassed those in dieldrin-treated houses. This continued through the year. By May, 1956, a year after application, *stephensi* was the predominant species in the 1955-DDT-treated houses. This was reflected in the malaria cases coming from the al-Hasa area in the spring of 1956; whereas in Qatif, by contrast, dieldrin was exercising far better control.

In February and March, 1956, a few anophelines, *pulcherrimus* and *coustani* var. *tenebrosus* but NOT *stephensi*, were found in the Qatif oasis in houses sprayed 5 to 6 months previously with 45 mg dieldrin/sq ft. The first *stephensi* to return to dieldrin-treated houses (at 45 mg/sq ft.) after the fall, 1955, application were found in certain gardens just west of Dammam. Here a number of *stephensi* were found in several different shelters in March, 6 months after dieldrin had been applied at a dosage of 45 mg/sq ft. In May, 1956, a few *stephensi* were found in 1955-treated shelters in the Qatif gardens. Later in June, *stephensi* was also found, but it was outnumbered by *pulcherrimus* which had previously been a very minor species in house collections. In comparable shelters sprayed with 90 mg dieldrin/sq ft, no anophelines were found during the 12-month period between dieldrin applications in 1955–56. This situation continued throughout the rest of 1956 until the entire area was resprayed in the fall by the Saudi Arab Government Ministry of Health team.

With the reappearance of anopheles on dieldrin-treated surfaces at a dosage of 45 mg/sq ft, recommendations were made for a higher dosage, to give a residue lasting preferably 10 to 12 months. Evidence was developed during 1956 that a dosage of 90 mg/sq ft would be effective for this period. No anophelines were found in shelters treated at this dosage in the 12-month interval between this application and the routine reapplication made by the Ministry of Health.

In the fall of 1956, the Ministry of Health took over the residual-spray program and continued the general use of dieldrin in both the Qatif and al-Hasa oases. An estimated dosage of 70 mg/sq ft was applied in their program in an attempt to get the most economic application to cover both fall, and subsequent spring, malaria seasons.

Although their program was not completed until January, 1957, the normal fall peak which began to develop in October was effectively stopped. As a result, 1956 November and December monthly morbidity rates dropped to 9/10,000 and 3/10,000, respectively. These were the lowest November-December rates recorded up to that time for our Saudi Arab employees. We feel that the complete spraying of both oases with dieldrin instead of DDT has been the primary reason for this remarkable decline in morbidity rates. Throughout 1957 and 1958, monthly rates have continued at minimal levels when compared with previous years (see Table 22).

LABORATORY CONFIRMATION OF DDT RESISTANCE

With overwhelming malariometric evidence for DDT resistance and supporting evidence from field entomological observations, we were most anxious to confirm the existence of DDT resistance by actual laboratory tests on *Anopheles stephensi*. In the fall of 1954, we requested from the World Health Organization a standard anopheline testing kit for using the modified Busvine-Nash technique in anopheline resistance studies (W.H.O., 1954).

Mr. G. Davidson, W.H.O. Consultant Entomologist, was invited to Saudi Arabia to compare our field reports on *stephensi* resistance with reports of other anopheline resistance (*i.e.*, *sundaicus*) in the Far East. Working with Dr. R. L. Peffly, Aramco's Entomologist, median lethal concentrations for DDT, dieldrin, gamma BHC, and aldrin were determined by the modified Busvine-Nash technique as recommended by W.H.O. Comparisons were made in November-December, 1955, between *stephensi* collected from a garden area at 'Ain-al-Saih which had never been subjected to DDT residual sprays, and from al-Mutairifi in the al-Hasa oasis where DDT applications were first applied in 1949.

These results, first summarized by Davidson (1955a) in a restricted W.H.O. report (later reviewed by Busvine, 1956 and 1957 and by Davidson, 1958), showed a 10-fold resistance in *stephensi* from an al-Hasa treated area when compared with *stephensi* from untreated 'Ain-al-Saih near Dhahran. This, then, was the final piece of evidence needed to confirm the existence of DDT-resistance in *Anopheles stephensi* in Saudi Arabia. No evidence for dieldrin resistance was found at this time.

More recent tests for dieldrin resistance repeated in 1957 and early 1958 have shown no significant changes for *stephensi*. However, some evidence is appearing to indicate dieldrin resistance in *Anopheles pulcherrimus* and in *A. coustani* var. *tenebrosus*. Details of these observations are to be published shortly by Dr. R. L. Peffly (1959).

PART VII. FUTURE MALARIA CONTROL IN THE EASTERN PROVINCE

The problems in future malaria control raised by our experience with DDT resistance are many and varied. If dieldrin resistance develops, it may be necessary to forego dependence on residual insecticides and re-emphasize the more classical methods of malaria control through environmental sanitation and water management. The use of newer drugs, particularly in combination with residual insecticides, may prove of great future importance. Greater emphasis on mechanical controls with screening and use of bed nets, on the use of natural enemies such as larvivorous fish, on drainage both for improved agriculture as well as mosquito control, and on intensified programs for malaria education of the public, all these must be currently reviewed in light of potential insecticide-resistance problems.

Residual Sprays Versus Larviciding

Although we have no evidence of resistance to dieldrin developing in *stephensi* at present, the danger that local *stephensi* may develop resistance to this insecticide is of great practical importance locally. Substitution of a larvicidal campaign throughout the entire oasis would be much more expensive than residual sprays and much more difficult to administer effectively. The enormous number and variety of breeding areas, the temporary and changing nature of many of them, and the wide areas to cover (many not readily accessible by road) with larviciding crews will make this a difficult and expensive operation.

Restricted larviciding, however, has a definite place in our malaria control measures, particularly in those villages which are not adjacent to, nor surrounded by, extensive irrigated areas. In these towns and villages, breeding areas are often restricted and very localized. Removing them by permanent control measures or placing them on a larviciding schedule will be much more economical than including the entire city or town in a residual-spray program.

Irrigation and Water Management

More attention to efficient construction and maintenance of irrigation systems is needed to reduce mosquito breeding areas, particularly seepage areas. Unnecessary ditches should be filled and reconstruction of irrigation systems along more modern lines should be attempted. In particular, stricter enforcement on proper construction of artesian wells must be instituted. The many uncapped, constantly-flowing artesian wells not only waste a valuable natural resource but contribute to an increased malaria hazard as well. These should be repaired and the hazard corrected.

Proper maintenance of irrigation canals and drains is especially important. Seepage areas should be prevented and corrected if they do occur. Drains should be kept free-flowing, stagnation should be prevented, and channels kept free of vegetation which would provide shelter for larvae and inhibit efficiency of fish predators.

Drainage

The extensive areas of water-logged land, with resultant detrimental effect on agricultural productiveness as well as on health, should be carefully studied. Knapp (1955) has recently reviewed the possibilities of agricultural drainage and its potential benefits in the Qatif oasis. Every effort should be made to encourage this drainage scheme for its malaria control advantages as well as for general improvement in agricultural productivity. Even minor drainage attempts by individual landholders throughout the oases would remove many smaller areas of mosquito breeding and provide additional productive agricultural land.

Filling

Many small anopheline breeding areas, particularly in and around villages, can be permanently removed by filling. Borrow pits, for example, can be utilized as sanitary land fills

by adjoining villages. Need for new borrowing should be regulated and care taken not to go below winter ground-water level. Abandoned shallow wells and nonfunctioning ditches can be filled. Shallow ponds and smaller seepages can be permanently eliminated as malaria hazards by this method.

Introduction of Larvivorous Fish

Greater use of larvivorous fish is indicated especially in isolated wells and ponds, in the new irrigation systems in newly developed gardens, and in isolated smaller oases. A native cyprinodont, *Aphanias* (*Lebias*) *dispar* Rüppell, is found very commonly in local irrigation systems both along the coast, on Bahrain Island, and at al-Hasa. The writer introduced this hardy species successfully in the al-Kharj area in the Najd in 1948. Wherever this fish occurs, it is an efficient predator on anopheline larvae; but its effectiveness is decreased where emergent vegetation and algal mats furnish protection to mosquito larvae. Hence, clearance of drains, irrigation channels, and wells is important for maximum effectiveness.

Gambusia affinis was brought in from Egypt by the writer some years ago. Colonies of this mosquito fish have been established in the Qatif area, and many additional plantings have been made. This species was introduced successfully in some of the larger wells and ponds in the Yabrin oasis in 1950. The same restrictions referred to above are applicable to *Gambusia* as far as effective larval control is concerned.

Health Education

Increased emphasis on malaria education will be even more essential for effective malaria control if residual-spray treatments are replaced by other measures or if malaria eradication becomes our objective. With residual-spray treatments, all that was necessary was to obtain cooperation of the villagers in allowing their premises to be sprayed. With eradication or with other control measures contemplated, intelligent participation, understanding, and cooperation of individual villagers in control and eradication efforts will be essential.

We have already taken steps to increase awareness of this fact in our malaria education programs. A 20-minute, 16-mm color, motion picture film entitled "The Battle Against Malaria" has been produced locally as part of the present study on oasis malaria. An illustrated pamphlet ("Malaria Control"), a film strip, and a series of eight colored posters (22″ x 29″) all in Arabic, have been developed during the course of this study as additional educational tools for informing the public. These materials are used not only in the Company's health education efforts with employees, but also in similar activities in the public schools in both oases. They are also made available to the Ministry of Health. More recently, the film, along with other special programs on malaria, has been broadcast in Arabic over the Company's new television station. Similar programs will be repeated from time to time, especially during the periods preceding maximum transmission seasons. All of these efforts are evidence of the important role we feel health education can play in promoting future malaria control or attempts at malaria eradication.

Malaria Eradication versus Malaria Control

With our local evidence of increased efficiency of dieldrin over DDT, it appears possible to aim for malaria eradication in our oases rather than only for malaria control. Our 1957 morbidity experience, together with November, 1957, parasite surveys, are particularly encouraging in this regard. Only 54 cases of malaria (42/10,000) occurred in Aramco employees in 1957. Of these, 48 (88.9%) were due to *vivax* and 1 (1.9%) to *malariae* infections. Only five *falciparum* infections (9.2%) occurred during the entire year. A parallel situation has already been reported for our November, 1957, village surveys, both in parasite rates (5.8%) for the 2–14-year age group and the zero infant parasite rates. The predominance of *vivax* (88.9%) in Aramco-employee infections and *malariae* in village surveys (57.1%) indicates that most of the currently reported cases are probably relapses rather than new infections. Most of these older infections show a light parasitemia[5]; hence infection of potential vectors is becoming increasingly more difficult. All this evidence points to future success if eradication efforts are properly organized and carried out.

[5] Of the 56 positive blood films among 1,058 examined in village surveys during November 1957, only three were noted as having "many" parasites; five were marked "few parasites found;" and in 48 cases, parasites were recorded as "rare." In only two of the 56 were gametocytes noted.

If subsequent infant parasite rates and autochthonous morbidity rates continue to show that transmission has almost ceased, then the importance of immigrants, small undiscovered foci of transmission, and possible remaining carriers must be especially considered in an eradication campaign.

Immigrants coming into the Eastern Province will be a most important problem in malaria eradication attempts as well as in maintaining the Province malaria-free if eradication is successful. The Arabian American Oil Company attracts large numbers of prospective employees from all parts of the Kingdom, as well as from other malarious areas in India, Pakistan, Trucial Oman, Muscat, Yemen, Syria, Lebanon, Somaliland, Sudan and others. Other developing industrial organizations utilize such potentially infected immigrants on a smaller scale. Fortunately, for the moment at least, these individuals are settling in the least malarious locations and in areas where intensive control measures can be most easily carried out. But these industrial immigrants, if they come from malarious areas, will remain a potential threat to eradication efforts unless adequate steps are taken to meet this hazard. In such controlled groups, it may be possible to institute routine drug treatment to prevent reintroduction of malaria through use of a single dose of 0.6 g chloroquine base with 50 mg of pyrimethamine as suggested by Macdonald (1957).

The migrations of local Bedouin tribes may also affect future malaria eradication efforts in the Qatif and al-Hasa oases. For the most part, Bedouins are not exposed to massive malaria infection. But, in their migrations it is possible for some individuals to contract malaria in small uncontrolled oases elsewhere in Saudi Arabia and later infect vector mosquitoes in either al-Hasa or Qatif on subsequent visits. Although this will probably be an uncommon source of reinfection of mosquitoes, it will be a most difficult one to control adequately.

The well-known Moslem pilgrimage will also tend to draw more temporary immigrants than ever before through the Eastern Province to pilgrimage centers in Mecca and Medina. With the completion of more modern sea and airport facilities and extension of the present Dammam-Riyadh railroad to Medina and Mecca, local pilgrim traffic with its potential malaria hazards will increase. Thus a greater number of pilgrims (and possible carriers) from Iraq, Iran, Pakistan, Afghanistan, and Bahrain may pass through our oases and continue to infect local anophelines unless special provision is made to prevent this occurrence. The implications of the pilgrimage on Kingdom-wide malaria eradication attempts have already been discussed by Farid (1956). Special care should be taken to make Dammam (the major port of the Eastern Province and present rail-head) anopheline-free; so there is no danger of parasite reintroduction in this sensitive area. Al-Khobar should also be included in an intensive mosquito control campaign because of its nearness to the major airport of the Province.

In spite of obvious difficulties and need for careful, long-term planning, the goal of malaria eradication in the Qatif and al-Hasa oases seems to be a practical one at the moment. Detailed epidemiological information is now at hand on which to base such a program, international funds are available to countries planning for eradication, and the benefits of such a campaign for eradication should be obvious to all. With respect to malaria eradication in the Eastern Province, we can agree with Russell (1956) in the statement: "Whereas formerly many communities could not afford to control malaria now they cannot afford NOT to eradicate it."

SUMMARY

1. Malaria has been an important health problem in the Qatif and al-Hasa oasis for centuries. The disease is sharply delimited to cultivated areas in the Eastern Province and affects the settled oasis population (310,000). The nomadic Bedouins are normally free of the disease.

2. Oasis malaria is man-made malaria and is directly connected with the local practice of agriculture. Local irrigation methods and drainage schemes furnish vector breeding places; hence malariousness of villages is directly dependent on their nearness to, and extent of, adjacent irrigated acreage.

3. Uncontrolled malaria may reach hyperen-

demic proportions. As such, it represents a major potential cause of morbidity and a ranking cause of mortality in the oases. Both industry and agriculture suffer when the disease is uncontrolled; and if these activities are to continue to prosper, adequate provision for malaria control must be made.

4. Precontrol morbidity (1941 through 1947) in adults was measured by cases reported in Saudi Arab employees of the Arabian American Oil Company. Annual attack rates varied from slightly over 1,000/10,000 in less malarious years to 2,300/10,000 in more malarious years. The mean annual morbidity rate in this group of adults was 1,631/10,000 during precontrol years.

5. Precontrol mortality (1941 through 1947) averaged 22/100,000 in the above employee group (only eight employee deaths). With 43 malaria deaths of patients from the general population occurring in Aramco hospitals during this same period, a proportionate mortality rate of 11.6 per cent was recorded. This rate was calculated from total deaths reported on death certificates in Saudi Arab employees, their dependents, and other non-Aramco members of the general public.

6. Precontrol malaria surveys (1947) in typical oasis villages in the Qatif area showed an average parasite rate (2–14-year age group) of 85 per cent. The infant parasite rate was 100 per cent. The gametocyte rate in the 0–11-month age group was 27 per cent; in the 12–23-month group, 24%; and for the 2–14-year composite, 13%. A comparable spleen rate in the 2–14-year age group was 94 per cent. Spleen rates increased with age; the reverse was true of parasite rates. The average spleen size was 2.2, average enlarged spleen was 2.3, and splenometric index was 217.1 in the 2–14-year age group. These data emphasize the public health importance of malaria in these oases.

7. *Falciparum* malaria was predominant over *vivax* and *malariae*, both in available adult morbidity data and in village parasite surveys of children. From original Qatif surveys in typical oasis villages, the 85 per cent parasite rate consisted of *falciparum*, 35.5 per cent; *vivax*, 27.4 per cent; *malariae*, 14.2 per cent; species undetermined, 1.2 per cent; and mixed infections, 6.6 per cent. The same general proportionate species distribution occurred among employee cases when species determinations were available. In earlier years, a majority of cases reporting to hospitals was determined as clinical malaria without reference to species of parasite.

8. The following anophelines occur in the area: *A. stephensi*, *fluviatilis*, *pulcherrimus*, *sergenti*, *multicolor*, and *coustani* var. *tenebrosus*. Of these *stephensi* is the only important vector; *fluviatilis* may be of secondary importance, but its role in local malaria transmission is unknown.

9. The local vector, *Anopheles stephensi*, is present in enormous numbers especially during spring and fall transmission seasons. It rests in man-made shelters during the day and is active in feeding only after sunset. Blood meal sources include a variety of warmblooded animals; but on the basis of limited precipitin test data, man is not the favored host. *Stephensi* accounts for 90.6 per cent of anophelines found in houses and for 79.3 per cent of anophelines recoverd from light-trap collections. The New Jersey electric mosquito trap has proved useful in local anopheline surveys.

10. *Stephensi* utilizes a wide variety of surface waters for breeding places. Among the more important are drainage ditches, seepage areas, ponds, shallow wells, borrow pits, and shallow puddles. Rice fields do not add appreciably to the local malaria problem. Artificial containers are of no local importance as *stephensi* breeding sites. High degrees of salinity and even some degree of pollution are not deterrents to breeding.

11. Local climate is characterized by extremely hot summers and temperate winters, with oppressively high humidity in late summer and early fall. Weather data from Aramco's Ras Tanura weather station were used in studying effects of climate on seasonal distribution of malaria and on vector densities. Mean weekly and monthly temperatures (1945–1956), mean weekly and monthly relative humidities (RH) based on 0900 readings (1945–1949), and on daily means (1949–1956) were calculated. Monthly rainfall data are available from 1945–1956. The average annual rainfall is 3.23 inches, occurring sporadically from November through May, with December having the highest average monthly rainfall (1.14 inches). Mean monthly temperatures for the 12-year period (1945–1956) ranged from a low of 60.7° F in January to highs of 92.5° F in July and August. Mean monthly RH based on 0900 readings (1945–1949) ranged from a low of 50.1 per cent in August to a high of 78.4 per cent in December. When calculated from daily

means (1949–1956), mean RH ranged from a low of 53.8 per cent in June to a high of 73.3 per cent in February. With wide daily fluctuations in humidity, 0900 readings and subsequent calculations from them gave a more orderly seasonal progression and recession in RH. Hence the latter are recommended for any future analysis of RH.

12. Winter temperatures are low enough to inhibit, but not severe enough to stop, *stephensi* breeding. Spring and fall provide ideal conditions for development of maximal seasonal population densities. April and October are peak months. The hot, dry summer is the most critical period in the seasonal life cycle of the vector, and lowest populations of the year are thus found from June through September. More favorable microclimates play an important role in protection from unfavorable extremes of temperature and humidity during this critical summer period.

13. Malaria morbidity occurs in a characteristic seasonal cycle with peak rates in spring (May) and fall (November). Hot summer months usually show lower malaria morbidity rates than do winter months. This seasonal distribution is controlled largely by temperature variations, with RH playing an important secondary role in summer and early fall. These combinations of temperature and humidity affect total vector population, individual vector longevity, infectivity of vector, development of parasite in the mosquito host, and seasonal behavior patterns in the human host. Rainfall is of little or no significance in seasonal distribution of local malaria.

14. Optimum malaria transmission occurs in October when mean monthly temperatures of 82° F and mean RH of 65 per cent or above occur. This represents an optimum temperature for the extrinsic incubation period of the parasite, and this temperature-humidity combination also favors vector longevity. Preceding optimal vector temperatures (90° F) have allowed maximum vector densities to be attained earlier. This results in a maximum transmission potential in October with maximal morbidity following in November. Cooler temperatures inhibit transmission, and reduced morbidity occurs during the winter months.

In spring, optimum temperatures are reached in late April and early May with favorable humidity declining to unfavorable levels before optimal vector developmental temperatures are reached. Hence, spring vector densities do not reach full potential as they do in the fall. As a result of this onset of hot, dry conditions, the spring malaria season is shorter and morbidity is less than in the fall. Unfavorable humidity (below 60% RH) along with increasing unfavorable temperatures decreases vector longevity, and transmission is cut sharply in June. Low midsummer morbidity follows, until a combination of optimum temperatures and favorable humidities reappear causing a sudden rise in transmission in October and peak morbidity in November to complete the seasonal cycle.

15. A standard seasonal pattern of malaria morbidity based on average temperature-humidity conditions is presented. Variations from this standard morbidity pattern can be predicted on the basis of preceding months' variations from average temperatures and RH. This is of potential practical importance in advance planning for treatment of cases if control measures are discontinued and seasonal epidemics reoccur. Thus, November will be more malarious than usual if October mean humidities are above the normal 65 per cent and approach 70 per cent or higher. If October temperatures remain abnormally high, the fall peak in morbidity may be delayed until December. In spring, if May RH remain favorable (60% RH or above) instead of beginning their normal decline toward early summer lows, a higher-than-normal June morbidity rate may be expected.

16. Residual sprays alone can control local malaria effectively. Annual applications of 200 to 250 mg/sq ft of DDT beginning in 1948 gave adequate malaria control until late 1953 when development of DDT resistance became apparent. This resistance prevented adequate malaria control in 1954 and 1955. Dieldrin replaced DDT as the insecticide of choice in 1955. Annual applications have since proved dieldrin more effective than DDT had ever been in reducing malaria morbidity. For best results, residual applications should be completed in September so that the insecticide deposit will be at maximum strength and effectiveness during the peak October transmission season. Any delays in application after this date will be reflected in higher morbidity rates in November and December. Such precise timing may be less important with longer-lasting dieldrin (over 12 months) but should be continued wherever possible. September

applications will insure treatment of all new dwellings or those missed the previous year before October transmission season begins.

17. DDT resistance became apparent in late 1953, five years after the first DDT application. Malariometric evidence, field vector observations, and laboratory confirmation are all offered in support of this resistance development. November morbidity rates rose to over 310/10,000 in the fall of 1953 and 1954; while in earlier years of successful DDT control, November rates ranged from 19 to 62/10,000. Infant parasite rates in experimental villages (al-Ajam and Safwa) during this same period rose from 0 per cent to 31.3 per cent in 1954. Parasite rates in these villages, varying from 1.0 per cent to 14.4 per cent in control years, increased to 44.9 per cent in 1954.

18. Entomological evidence from the field showed progressively shorter intervals in return of *stephensi* to DDT-treated shelters. After the initial 1948 application, about 12 months elapsed before *stephensi* were first collected on sprayed surfaces; and then in much reduced numbers compared to untreated checks. After a second application, a 5-month interval was noted; and by 1954, only 2 months elapsed. Unfortunately, 24-hour mortalities were not observed in these checks.

19. Laboratory determination of median lethal concentrations for *stephensi* from areas where DDT had been first used 5 and 6 years previously showed a 10-fold resistance to DDT had developed. This was taken as final confirmation that DDT resistance had occurred to an extent that DDT was failing to give adequate malaria control.

20. Dieldrin applied at a dosage of 50 to 70 mg/sq ft has successfully replaced DDT in local malaria-control campaigns. It is a more effective residual insecticide as shown by reduction of morbidity and parasite rates to the lowest levels since control programs were instituted.

21. Success of the residual-spray technique alone in controlling malaria is shown by comparison of the precontrol morbidity mean of 1,631/10,000 in Aramco Saudi Arab employees (1941–1947) with the 1958 annual rate of 28.5/10,000. A maximum precontrol rate of 2,317/10,000 was recorded in 1943. In village surveys, infant parasite rates in both oases dropped from 100 per cent in 1947–48 to 0 per cent in 1957. Overall parasite rates (2–14-year age group) in the Qatif oasis dropped from 85 per cent to 6.4 per cent. Most of the recent clinical and parasite relapses are *vivax* (Aramco employees) or *malariae* (village children) infections. This indicates the possibility that relapses rather than new infections are responsible for most of those cases currently being seen. Overall spleen rates in the Qatif oasis (2–14-year) age group declined from 94 per cent to 3.8 per cent; average spleen size from 2.2 to 0.05; average enlarged spleen from 2.3 to 1.4 and splenometric index from 217.1 to 5.3. Thus, the residual-spray technique alone (with dieldrin as the insecticide) can adequately control malaria; and may be able to eradicate the disease in these oases if dieldrin resistance does not develop.

22. Potential dieldrin resistance makes it imperative to review application of classical malaria-control techniques to our local malaria problem. Larviciding presents problems of labor, administrative control, and increased costs. Improvements in water-management techniques offer the greatest field for mosquito-malaria-control efforts. More efficient construction, maintenance, and repair are needed for irrigation channels and drains to prevent surface water accumulations. Proper construction and valve control of artesian wells should be enforced. Drains should be kept free of vegetation and water free-flowing.

23. A general scheme for agricultural drainage already proposed should be expedited for malaria control as well as for increased agricultural productivity. Ponds and swamps should be drained and general ground-water levels lowered. Smaller breeding areas such as abandoned ditches, shallow wells, and borrow pits should be filled. Larvivorous fish should be introduced wherever practicable.

24. Individual understanding and participation in control efforts through health education should be expanded. A locally-produced film and filmstrip, posters, brochures, and school lesson plans have been made available for such programs. A recently inaugurated, local, television program is already being used to help meet these health education objectives.

25. Malaria eradication is a practical and economically desirable goal if the above control measures are fully implemented. Our most recent morbidity data and parasite surveys (1958) encourage this attempt. Special care in surveillance, reporting and investigating of individual cases will become of increased importance with con-

tinued influx of industrial immigrants. Pilgrims will also make increasing use of newly developing seaports, airports, and cross-country railways of the area for the Mecca pilgrimage. Movements of Bedouins from uncontrolled areas into the eradication zone will also present problems. In spite of obvious difficulties and need for careful, long-term planning and financing, malaria eradication is recommended as an ultimate achievable goal.

ACKNOWLEDGMENTS

This study could not have been undertaken without the active support of the Arabian American Oil Company and its Medical Department, particularly Dr. R. C. Page, Medical Director, who has given advice and encouragement over the several years spanned by the project. To specific individuals within the Preventive Medicine Division go the writer's appreciation for special assistance: to Mr. D. J. Strait, formerly Entomologist, for assistance both in early malaria surveys and in carrying out the first residual-spray programs; to Dr. R. L. Peffly, Entomologist, for continuing these projects plus his special contribution of laboratory tests on anopheline resistance to insecticides; to Miss Marjorie E. Haydon, Medical Technologist, and her staff for field and laboratory work in preparing and reading survey blood films; to Mr. M. V. Owens, Health Educator, for assistance in developing health-education materials on malaria; to Mrs. Bernice Scully for her assistance in tabulating morbidity, mortality, survey and climatological data; and to Miss Lois Snyder, Medical Secretary, for her capable and careful preparation of the manuscript both in the several drafts and in the final format.

Finally, the writer wishes to express his appreciation to Dr. Thomas H. Weller, Harvard School of Public Health, for his valuable suggestions during the preparation of the material as a doctoral thesis and in its presentation for publication.

REFERENCES

Abdel-Malek, A., 1956. Mosquitoes of north-eastern Sinai (Diptera: Culicidae). *Bull. Soc. Entom. Egypte*, **60:** 97–107.

Afridi, M. K., and Majid, A. S., 1938. Malaria in Bahrein Islands (Persian Gulf). *J. Mal. Inst. India*, **1:** 427–472.

———, Singh, J., and Singh, H., 1939. Food preferences of *Anopheles* mosquitoes in the Delhi urban area. *J. Mal. Inst. India*, **2:** 219–227.

Bana, F. D., 1943. A note on the adaptability of *Anopheles stephensi* to breed in salt water in Bombay, with some observations on larvivorous fish. *J. Mal. Inst. India*, **5:** 123.

Busvine, J. R., 1956. Significance of insecticide resistant strains. *Bull. World Health Organ.*, **15:** 389–401.

———, 1957. Insecticide resistant strains of insects of public health importance. *Tr. Roy. Soc. Trop. Med. & Hyg.*, **51:** 11–31.

Buxton, P. A., 1944. Rough notes: anopheles mosquitoes and malaria in Arabia. *Tr. Roy. Soc. Trop. Med. & Hyg.*, **38:** 205–214.

Chalam, B. S., 1926. The breeding of anopheles in seawater and at a short distance from the shore. *Indian M. Gaz.*, **61:** 375–376.

———, 1927. The resistance of anopheline eggs to desiccation. *Indian J. M. Res.*, **14:** 863–866.

Covell, G., 1944. Notes on the distribution, breeding places, adult habits, and relation to malaria of the anopheline mosquitoes of India and the Far East. *J. Mal. Inst. India*, **5:** 399–434.

———, Russell, P. F., and Swellengrebel, N. H., 1953. Malaria terminology. *World Health Organ., Mon. Ser.*, **13:** Geneva, 82 pp.

Daggy, R. H., 1957. Oasis malaria, *Industry and Tropical Health III:* 42–55, Harvard School of Public Health, Boston.

Dakshinamurty, S., and Sharma, M. I. D., 1951a. The temperature preference of mosquitoes. *Indian J. Malariol.*, **5:** 221–227.

———, 1951b. The humidity preference of mosquitoes. *Indian J. Malariol.*, **5:** 209–219.

Davidson, G., 1955a. Report on a visit to Saudi Arabia regarding insecticide resistance of *Anopheles stephensi*. *World Health Organ., MH/AS/17.56* (mimeographed).

———, 1955b. The principles and practice of the use of residual insecticides for the control of insects of medical importance. *J. Trop. Med.*, **58:** 73–80.

———, 1958. Studies on insecticide resistance in anopheles mosquitoes. *Bull. World Health Organ.* **18:** 579–621.

———, Ramsdale, C. D., and Edwards, B. V., 1957. An attempt to induce DDT-resistance in a colony of susceptible *Anopheles stephensi*. *Tr. Roy. Soc. Trop. Med. & Hyg.*, **51:** 293–294.

Farid, M. A., 1956. Implications of the Mecca pilgrimage for a regional malaria eradication program. *Bull. World Health Organ.*, **15:** 821–828.

Giles, G. M., 1906. Mosquito notes I. Notes on a small collection of mosquitoes from Bahrein

in northern Arabia (shores of Persian Gulf). *J. Trop. Med.*, **9:** 130–132.

GILL, C. A., 1921. The role of meteorology in malaria. *Indian J. M. Res.*, **8:** 633–693.

———, 1938. *The Seasonal Periodicity of Malaria and the Mechanism of the Epidemic Wave.* J. A. Churchill Ltd., London, 136 pp.

GRAMICCIA, G., DE MEILLON, B., PETRIDES, J., AND ULRICH, A. M., 1957. *A. stephensi* resistance to DDT in southern Iraq. *WHO/EM/Mal./Erad./31* (Dec. 7, 1957, mimeographed).

HACKETT, L. W., 1944. Spleen measurement in malaria. *J. Nat. Malaria. Soc.*, **3:** 121–133.

HADAWAY, A. B., AND BARLOW, F., 1953. Studies on aqueous suspensions of insecticides. Part IV. The behavior of mosquitoes in contact with insecticidal deposits. *Bull. Entomol. Res.*, **44:** 255–271.

———, 1957. The influence of temperature and humidity upon action of insecticides I. During the post-treatment period. *Ann. Trop. Med. & Parasitol.*, **51:** 187–193.

HORSFALL, W. R., 1955. *Mosquitoes, Their Bionomics and Relation to Disease.* Ronald Press, New York, 723 pp.

HUSAIN, M. Z. Y., AND TALIBI, S. A., 1956. Incrimination of the vector of malaria in federal Kerachi area (Pakistan). A record of dissections of anopheline mosquitoes carried out by the Malaria Institute of Pakistan. *Pakistan. J. Health.*, **6:** 65–72 (*R.A.E. 46:* 3, 1958).

KNAPP, F. H., 1955. Drainage report on Qatif area, typewritten report. Arabian American Oil Co., Dhahran, Saudi Arabia.

KNOWLES, R., AND BASU, B. C., 1943. Laboratory studies on the infectivity of *Anopheles stephensi*. *J. Malariol. Inst. India*, **5:** 1–29.

KRISHNAN, K. S., 1954. Malaria vectors of India. IV. *A. stephensi* Liston, 1901. *Bull. Nat. Soc. India, Mal. other Mosq.-Borne Dis.*, **2:** 98–109.

LAL, R., 1953. Notes on the effect of temperature on the developmental stages of *Anopheles subpictus* Grassi and *Anopheles stephensi* Liston. *Indian J. Entomol.* **15:** 97–106.

LEESON, H. S., 1948. Anopheline larvae collected in Arabia, *Ann. Trop. Med. & Parasitol.*, **42:** 253–255.

———, LUMSDEN, W. H. R., YOFE, J., AND MACAN, T. T., 1950. Anopheles and malaria in the Near East. *Mem. Lond. Sch. Hyg. & Trop. Med.*, **7:** 233 pp.

MACDONALD, G., 1956. Epidemiological basis of malaria control. *Bull. World Health Organ.*, **15:** 613–626.

———, 1957. *The Epidemiology and Control of Malaria.* Oxford University Press, London, 201 pp.

———, AND DAVIDSON, G., 1953. Dose and cycle of insecticide applications in the control of malaria. *Bull. World Health Organ.*, **9:** 785–812.

MATTINGLY, P. F., AND KNIGHT, K. L., 1956. The mosquitoes of Arabia. I. *Bull. Brit. Mus. (Nat. Hist.) Entomol.* **4:** 91–141.

MAYNE, B., 1930. A study of the influence of relative humidity on the life and infectibility of the mosquito. *Indian J. M. Res.*, **17:** 1119–1137.

MOFIDI, C., SAMIMI, B., AND GHIASSEDDIN, M., 1958a. Further studies of anopheline susceptibility to insecticides in Iran. 2. Results of W.H.O. adult mosquito test method. *WHO/Working paper/ES/IR/Seminar/17/Add. 3* (mimeographed).

———, ESHGI, N., GHIASSEDDINE, M., AND RASHTI M. S., 1958b. Further studies of anopheline susceptibility to insecticides in Iran. 1. Results of the Busvine-Nash method. *WHO/Working paper/ES/IR/Seminar/17/Add. 6* (mimeographed).

MUIRHEAD-THOMSON, R. C., 1951. *Mosquito-behavior in Relation to Malaria Transmission and Control in the Tropics.* E. Arnold and Co., London, 219 pp.

PAL, R., 1943. On the bionomics of *Anopheles culicifacies* Giles. Part I. Longevity under controlled conditions of temperature and humidity. *J. Mal. Inst. India.*, **5:** 77–85.

———, SHARMA, M. I. D., AND KRISHNAMURTHY, B. S., 1952. Studies on the development of resistant strains of houseflies and mosquitoes. *Indian J. Malariol.*, **6:** 303–316.

PEFFLY, R. L., 1959. Insecticide resistance in anopheles in Eastern Saudi Arabia. *Bull. World Health Organ.* In press.

PRINGLE, G., 1954. The identification of the adult anopheline mosquitoes of Iraq and neighbouring territories. *Bull. Endemic Dis.*, **1:** 53–76.

———, AND GARRETT-JONES, C., 1957. Additions to the *Anopheles* fauna of Iraq: *A. sergenti* Theobald and *A. apoci* Marsh. *Bull. Endemic Dis.*, **2:** 88–91.

RAJAGOPALAN, N., VEDAMANIKKAM, J. C., AND RAMOO, H., 1956. A preliminary note on the development of resistance to DDT by larvae of *Anopheles stephensi* type in Erode Urban, South India. *Bull. Nat'l. Soc. India, Mal. other Mosq-Borne Dis.*, **4:** 126–128.

ROY, D. N., 1931. The natural breeding habits of *A. stephensi* as observed in Calcutta. *Indian J. M. Res.*, **19:** 617–628.

———, CHANDRA, S. N., AND SIDDONS, L. B., 1938. On the presence of a zoophilic race of *A.*

stephensi in Calcutta. *J. Mal. Inst. India*, **1**: 417–426.

RUSSELL, P. F., 1956. *Now is the time*. WHO Newsletter, Special Issue on Malaria Eradication, Geneva.

———, AND MOHAN, B. N., 1941. An insectary colony of *A. stephensi mysorensis*. *Indian M. Gaz.*, **76**: 219–220.

———, AND RAO, H. R., 1940. The anopheles of ricefields in southeastern Madras. *J. Mal. Inst. India*, **3**: 427–446.

SIDDONS, L. B., 1944. Observations on the influence of atmospheric temperature and humidity on the infectivity of *Anopheles culicifacies* Giles. *J. Mal. Inst. India*, **5**: 375–388.

SINTON, J. A., AND SHUTE, P. G., 1938. A report on the longevity of mosquitoes in relation to transmission of malaria in nature, *London Min. Health. Rep. Publ. Health. & Med. Subj.*, **85**: 1–45.

SONTHINAND, U., 1952. Malaria control news note from Chiengmai Office, Thailand. *Trop. Med. & Hyg. News*, **1**: 15.

STRATMAN-THOMAS, W. K., 1940. Influence of temperature on *Plasmodium vivax*. *Am. J. Trop. Med.*, **20**: 703–715.

STRICKLAND, C., ROY, D. N., AND CHAUDHURI, H. P., 1933. A year's observations in Calcutta on the invasion of the salivary glands of *Anopheles stephensi* by malarial sporozoites, and the influence of some climatic conditions. *Indian J. M. Res.*, **20**: 819–840.

———, 1936. The prevalence and habits of anophelines in relation to physical conditions, with a statistical analysis. *Riv. malariol.*, **15**: 171–186.

SWEET, W. C., AND RAO, B. A., 1937. Races of *A. stephensi* Liston, 1901. *Indian M. Gaz.*, **72**: 665–674.

TARIZZO, M. L., 1957. Saudi Arabia-epidemiological notes on the Eastern Province. *Am. J. Tr. Med. & Hyg.*, **6**: 786–804.

VIDAL, F. S., 1955. *The Oasis of al-Hasa*. Arabian American Oil Co., Dhahran, Saudi Arabia, 216 pp.

WORLD HEALTH ORGANIZATION, 1954. Instructions for the use of test outfits in determining the effectiveness of insecticides against mosquitoes. *M.H./AS/99-54*, mimeographed, World Health Organ., Geneva.

———, 1954. Technique for assessing anopheline susceptibility to insecticides, 5th Report, Expert Committee on Malaria. *World Health Organ. Tech. Rep.*, **80**: 30.

ZAHAR, A. R., AND DABBAGH, H. S., 1957. A malaria survey in north western part of Saudi Arabia. *EM/Mal. Erad./7 Dec.*, 1957, mimeographed, World Health Organ., Geneva.